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Active

Project #: D-48-A86 Cost share #: D-48-346 Rev #: 5
Center # : 10/24-6-R8091-0A0 Center shr #: OCA file #: 241
Work type : RES
Contract#: R55677 Mod #: C Document : DO
Prime #: BCS-9025010 Contract entity: GTRC

Subprojects ? : N CFDA: N/A
Main project #: PE #: N/A

Project unit: DEAN ARCH Unit code: 02.010.170
Project director(s):
FRENCH S P DEAN ARCH (404)894-2350

Sponsor/division names: STATE UNIV OF NEW YORK / BUFFALO, NY
Sponsor/division codes: 400 / 051

Award period: 930901 to 960229 (performance) 960331 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	60,000.00
Funded	0.00	60,000.00
Cost sharing amount		11,371.00

Does subcontracting plan apply ?: N

Title: ESTIMATING SOCIETAL IMPACTS OF INFRASTRUCTURE DAMAGE THROUGH GIS

PROJECT ADMINISTRATION DATA

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Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
Defense priority rating : N/A N/A supplemental sheet
Equipment title vests with: Sponsor GIT X
>$10,000 REQUIRES SPONSOR NOTIFICATION. (SEE MASTER AGRMT EXH. A & NSF ART 6)
Administrative comments -
AMENDMENT C EXTENDS PERIOD OF PERFORMANCE TO 2/29/96, AND CHANGES DUE DATES
FOR TECHNICAL AND FINANCIAL REPORTS.

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

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NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 02/29/96

Project No. D-48-A86 Center No. 10/24-6-R8091-0A0

Project Director FRENCH S P School/Lab DEAN ARCH

Sponsor STATE UNIV OF NEW YORK/BUFFALO, NY

Contract/Grant No. R55677 Contract Entity GTRC

Prime Contract No. BCS-9025010

Title ESTIMATING SOCIETAL IMPACTS OF INFRASTRUCTURE DAMAGE THROUGH GIS

Effective Completion Date 960229 (Performance) 960331 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	950919
Final Report of Inventions and/or Subcontracts	Y	
Government Property Inventory & Related Certificate	N	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

Comments

Subproject Under Main Project No.

Continues Project No.

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other	N
	N

NOTE: Final Patent Questionnaire sent to PDPI.

D-48-A86
1

National Center for Earthquake Engineering Research

Mid-Term Review
July 1994

1. IDENTIFICATION DATA

Investigator: Dr. Steven P. French

Title: Estimating Societal Impacts of Infrastructure Damage with GIS

Duration: One year, $60,000

Match Funds: Georgia Institute of Technology - $11,371,

2. TECHNICAL DESCRIPTION OF EFFORT

The basic approach of this project is to use the GIS software to integrate demographic data with infrastructure. The research questions of the research involve understanding how the new spatial analysis capabilities of geographic information systems (GIS) be employed to estimate societal impacts of infrastructure damage caused by earthquakes. This first year considered two types of infrastructure: water distribution systems and high pressure gas lines. Development of actual GIS software and procedures was chosen as the best vehicle to explore these issues. The Memphis area was chosen because it has relatively high seismicity and has been the focus of fairly intensive study by previous NCEER researchers. This allowed the project to focus on the societal impacts drawing upon earlier NCEER earth science and engineering research.

The technical objectives of this project were to identify the best sources of data to support societal impact estimation and then to develop procedures for associating this data with various infrastructure systems. Once this is done it is possible to identify the size and characteristics of the population at risk from the failure of various infrastructure components. The Arc/Info GIS software running on a Sun Workstation was chosen as the appropriate platform for this analysis due to the sophistication of its network analysis and other spatial analysis function. This project tested a number of spatial analysis techniques to link population to the network. In the case of high pressure gas lines, a simple proximity buffer was used to identify the population at risk to explosion in the case of gas line rupture. In the case of the more complex network structure of a pressurized water distribution system, more sophisticated techniques are required. Initial efforts have used simple population and housing unit counts. The year one research has identified a richer set of societal indicators that are available for somewhat larger areas (census block groups). These indicators can be used to characterize the impacts on particular population subgroups. Recent research on the Northridge Earthquake and Hurricane Andrew indicate that the impacts of disasters impact different income and ethnic groups to different degrees.

This project began in October 1993. In its first nine months the project has developed procedures to estimate the type and size of population impacted by infrastructure system failures. Meeting these technical objectives required the research team to acquire existing GIS data at the metropolitan scale. This data described ground shaking, secondary hazards water distribution and high pressure gas lines for Memphis area of Tennessee. Dr. Howard Hwang, a previous NCEER researcher provided much of the earth science and engineering data to support the research. Dr. Masanobu Shinozuke, another NCEER researcher, provided us with the LIFELINE-W model for simulation of damage and flow estimation. This software provides damage and flow simulation under alternative earthquake scenarios. Our software can use the out put of this model to determine type and location of probable damage under several alternative earthquake scenarios. The team has developed spatial analysis techniques to associate small area demographic data on a map of urban infrastructure damage.

Software algorithms have been developed to prioritize the water line repair based on the service population of each component. A separate set of procedures is under development to estimate the number and characteristics of the population at risk to both gas line rupture and water system damage. These software tools were developed using the Arc/Info geographic information system and are compatible with the damage and flow analysis models developed by Shinozuka, Tanaka and Hwang (1993).

The project has produced or currently has underway the following products:

The year one technical report is in draft form and will be completed by the October 1 contract end date.

A draft of the users guide for using pipe restoration algorithms developed for this project.

Digital files containing raw and network linked demographic data are available. An Arc/Info AML for prioritizing pipe restoration is available in beta form

3. EXTENT OF TEAM APPROACH

It would not have been possible to do this project within the allotted budget without the help and support of other NCEER researchers. Dr. Howard Hwang was kind enough to provide digital GIS files of ground shaking, secondary hazards, infrastructure networks and political boundaries for Shelby County, Tennessee. Dr. Masanobu Shinozuka for the use of the LIFELINE -W earthquake damage and flow analysis model. Professor Shinozuka's staff has provided support foe the installation and use of the LIFELINE-W model. Our demographic analysis and pipe repair software are designed to utilize the pipe damage and water system node pressure data produced by the LIFELINE-W model as an input.

The following students have been involved with this research:

Xudong Jia, Ph.D. anticipated June 1996
Paul Goldsman, Ph.D anticipated June 1996
Elizabeth Meyer, Master of City Planning anticipated June 1995
Sanjay Grover, Master of City Planning anticipated June 1995
Kevin Edwards, MS anticipated December 1994

Have discussed this research and its possible application to the work of other NCEER researchers including:

Dr. Harold Cochrane
Dr. Barclay Jones
Dr. Kathleen Tierney
Dr. Howard Hwang
Dr. Masanobu Shinozuka

The Principal Investigator is a member of the Project Oversight Committee of the FEMA Earthquake Loss Estimation Project. Approaches developed in this project have been shared with this group.

4. ASSESSING THE QUALITY OF NCEER RESEARCH

This project links the center's lifeline research with its efforts to estimate societal impacts. This provides a critical link between the engineering research on critical lifeline systems and those responsible for emergency management and hazard mitigation. The effort is valuable to the scientific community because it explores and applies the use of newly developed GIS technology to the earthquake risk problem. This is the first effort to use this technology to integrate demographic data with engineering analysis of networked systems. It is valuable to the practitioner community because it identifies the types of demographic data that can be used to access societal impacts. It also develops useful software that can be used to prioritize repair or hazard mitigation projects based on the size and characteristics of their service populations. This software was developed to use demographic data from the 1990 Census and should, therefore, be applicable in any US. area subject to seismic hazards.

Refinements of this basic approach should be useful in assessing the societal impacts of other natural hazards, particularly floods. The project will explore the applicability of the techniques and software developed in this project to the water system damage caused by the summer 1994 floods in south Georgia.

The NCEER umbrella was important to this project in several ways. First, it made available advanced engineering models and expertise not included on this team. Second it provides a forum to explore how the results of this research can best be structured to meet the input requirements of other social science researchers. The techniques developed here should be especially useful to those interested in identifying the economic impacts of earthquake infrastructure damage.

5. INFORMATION DISSEMINATION AND TECHNOLOGY TRANSFER

The investigator has delivered two conference presentations:

"Estimating Societal Impacts of Infrastructure Damage through GIS," Natural Hazards Research Symposium: Translating Research into Practice, May 31- June 2, 1994, Louisville, KY, sponsored by the Central United States Earthquake Consortium

"Information Technology and Hazards Management," 19th Hazards Research and Applications Workshop, July 17-20, 1994, Boulder, Colorado.

An article for a scholarly journal will be developed based on the year one report.

Discussion with the Central United States Earthquake Consortium on making the model and data available to one or more users in the New Madrid area.

D-48-A08
#2

ESTIMATING SOCIETAL IMPACTS OF INFRASTRUCTURE DAMAGE WITH GIS

by

Steven P. French
and
Xudong Jia

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Interim Report

Project R55677
National Center for Earthquake Engineering Research
State University of New York at Buffalo
Buffalo, NY

ABSTRACT

This report describes a GIS model designed to estimate the societal impacts of infrastructure damage from earthquakes. The model links physical components of a water delivery system to population and economic data from the U.S. Census. A prototype model has been developed and implemented for the water distribution system of Memphis/Shelby County, Tennessee. There are three components of the model: the simulation module, the assessment module and the repair module. In the simulation module, damage to the system is specified in one of three ways. Either the user indicates the damaged links interactively or the output of a separate damage model is downloaded into the module. Once the simulation module is run, the assessment module presents the impacts of the damage in terms of specified demographic variables (e.g., How many people lost service? How many people over 65 lost service?). The repair module generates a priority list of water lines to be repaired to maximize service to user selected population groups (e.g., total population or population over 65 years old). This project combines contemporary understanding of societal impacts of disaster, research into the behavior of lifeline systems in earthquakes and state-of-the-art GIS technology.

CONTENTS

INTRODUCTION[1]

Current earthquake infrastructure damage models typically produce damage estimates that are expressed in terms of physical damage. For example, in the water distribution area the ATC-13 methodology produces estimates of the number of breaks per kilometer (Applied Technology Council 1986). While this information is useful, it does not fully meet the needs of emergency preparedness and hazard mitigation planners. What is needed is a way to translate this physical damage into its resultant impacts on society. The purpose of this project is to develop techniques for estimating the size and characteristics of population impacted by earthquake damage to urban infrastructure systems. Such social impact information can be used to allocate emergency response resources in the most effective manner and to set priorities for hazard mitigation efforts.

Current state-of-the-art infrastructure damage models use geographic information systems (GIS) to estimate earthquake damage. (For an excellent review of damage modeling techniques, see Risk Management Software and California Universities for Research in Earthquake Engineering 1994.) The GIS provides important advantages because it can handle large amounts of spatially distributed information and improve modeling by combining geotechnical information with system characteristics based on location. Typically, this type of modeling produces an estimate of the number of physical breaks in the system or an estimate of direct economic damage.

This social impact model links components of the physical system (e.g. individual water lines or pump stations) to small area population data. The GIS is used to associate block level demographic information from the 1990 Census of Population and Housing with nodes on the water distribution network. The GIS can then estimate the number and characteristics of people impacted by infrastructure damage at various locations based on the topological relationships of the distribution network. This makes it possible to characterize the societal impacts of infrastructure damage more precisely in terms of the affected populations.

This model provides the user with two alternative ways to specify the damaged condition of the water system network. The user may indicate the links that have actually been damaged in a real-time application. The system can accept a damage scenario generated by a separate water system damage data model. At this time we have developed software links to Lifeline(W), the model developed by Shinozuka and Hwang for the Memphis metropolitan area (Shinozuka, Tanaka and Hwang, 1993).

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[1]This research was supported by National Center for Earthquake Engineering Research Grant 93-6004.

The assessment module translates this physical damage to the water system into the number of people and housing units affected by the damage. The model uses block level demographic information from the 1990 Census of Population and Housing that is linked to the water network. As a result each link in the water distribution network is characterized by its service population in various categories.

To support real-time system repair or to prioritize earthquake mitigation expenditures, the societal impact model includes a routine that ranks the pipe segments to be repaired based on the population served by each segment. This allows an emergency manager or hazard mitigation planner to identify the damaged pipe segments that service the most population. These software tools were developed using the ARC/INFO geographic information system. The model also allows the user to focus on selected population characteristics as well as size. For example, the model can identify those segments that serve the most elderly population. The model is also useful for estimating the number and type of users subject to service interruption.

Before discussing the model itself, a brief review of current research on societal impacts of disaster, physical damage to infrastructure and repair processes will be useful. This work presents the foundations of this research project from a variety of disciplines and highlights the importance of understanding the social as well as physical impacts of the earthquake hazard.

LITERATURE REVIEW

Disaster planning, including earthquake mitigation and recovery, has long been considered a technical pursuit; building better buildings and stronger infrastructure has been the primary response to this hazard. However, the field is expanding beyond physical elements to include the social and economic impacts of disasters, as well as the process of recovery from them. In 1982, the Earthquake Engineering Institute recommended "analyses of social costs and benefits involved in mitigating and responding to earthquake disasters" (EERI 1982). The problem is that sociological and technical research efforts have remained separate (Tubbesing 1993). As our understanding of disasters' societal impacts increases, it is important to link engineering and social science research to provide the greatest possible benefits. EERI recommends social and policy scientists work more closely with the engineering community in order to develop appropriate repair and retrofit standards (Tubbesing 1993). This research project attempts to move in this direction by combining state-of-the-art GIS modeling technology with the most current views of the societal impacts of disasters.

Physical Damage

In any meaningful analysis, all of the pertinent information about societal and psychological impacts must begin with understanding of the physical damage earthquakes cause to infrastructure systems. Damage to lifelines should be thought of in terms of service outage, not in terms of damage to specific physical structures (Panel on Earthquake Loss Estimation 1989). This can be complex since lifeline systems generally cover a large area, and they are subject to a wide variety of seismic forces within the same system (Shah and Benjamin 1977). As is true for the social structures of communities, studies of actual physical damage experiences indicate that disasters tend to exacerbate existing infrastructure problems (United Nations Center for Regional Development 1990). This parallel underscores the value of proactive disaster planning and mitigation. To do this, it is essential to accurately predict the effects of earthquakes or other disasters on existing systems.

Honegger (1991) establishes the connection between Peak Ground Acceleration (PGA), soil types and earthquake damage. A process developed by Perkins (1992) for estimating housing damage uses this knowledge to prepare census tract level estimates of demand for emergency shelters. The results of the Perkins model were compared to the actual damage experienced in the Loma Prieta earthquake and were found to be reasonably accurate although more damage occurred on poor soils than would have been predicted. Earlier efforts to prioritize bridge retrofitting in Memphis and Shelby County, Tennessee combine the information on seismicity and site characteristics with knowledge of the structural characteristics of the bridges and their importance to the transportation in the region (Pereshk 1993).

GIS based models have been developed to estimate damage to buildings (Emmi & Horton 1993; French & Isaacson 1994; Patel 1991; Scawthorn, 1986) and damages to water delivery systems (Sato & Shinozuka 1991). These models effectively integrate information about the separate causes of physical damage. In order to create a system which may be used to recommend repair or retrofitting strategies, estimated damage is only one pertinent factor. As seen in the modelling of bridge damage, knowledge of the systems functioning is also crucial.

Social Impacts

In his seminal work, Eugene Haas studied communities before and after disasters to identify the factors that affected physical, housing, employment and family recovery. He developed a model that divided recovery into four phases: emergency response, restoration, replacement/reconstruction, and commemorative/betterment. Further, he identified pre-disaster community values, power structure and social structure as important determinants of the speed and shape of recovery (Haas et. al. 1977). Critiques of Haas' four phases have arisen. These criticisms were summarized by Bolin (1993), "recovery is best seen as a complex social process dependent both on material conditions rendered by the disaster and the complex array of political, economic and social forces existing before and after the disaster."

Bolin's study of household recovery from the Whittier Narrows earthquake indicates that recovery can be understood by the analysis of discrete components of a society, a household or a personality (Bolin 1993). His earlier work indicated that the psychological impact of disaster was dependent on factors such as suddenness of impact, scope of impact, length of warning, threat of recurrence, and exposure to death (Bolin 1988).

For this research project, the above studies establish a framework for considering societal impacts as a function of discrete elements that can be isolated and understood. Any of these elements which can be linked to demographic characteristics can be incorporated into our model.

There are clear indications that different groups within a society respond differently to disaster. In Bolin's Whittier Narrows study, he found that Hispanic victims were less likely to leave the area, even if their homes were heavily damaged. Most of the minority victims were poor, and there was a shortage of substitute housing which they could afford (Bolin 1993). If poor victims are unlikely to relocate, and a given disaster impacts low-income areas, this "invisible city" could be less impacted, and restoring lifeline service to the heavily damaged area may be more pressing.

Psycho-social impacts of disasters on the elderly have also received considerable attention. Bolin discovered that, compared to other age groups, the elderly recover quickly from the initial emotional impact, but they often experience a substantial decline in their standard of living (Bolin 1982). Later surveys of survivors of the Trinity River Flood in Texas found that age was not a significant predictor of post-disaster stress levels or depression (Tobin 1992). Other predictors were isolated however. Tobin found that the more people who lived in a household, the higher the stress levels of individual members; and that the more experience an individual had with disaster, the more depression was experienced. Significantly, Tobin also determined that the people who experienced the most depression before a disaster were more depressed after the disaster, and that people in poor health experienced higher stress levels (Tobin 1992). Therefore, while age alone may not have indicated more severe impact of disaster, age may be the most reliable demographic data with which to predict populations in poor health or experiencing depression.

The finding that pre-disaster conditions directly predict post-disaster conditions applies to societies as well as individuals. Thriving communities recover quickly (*Rebuilding After Earthquakes* 1991). In fact, the most striking need people have after a disaster is a need for normalcy (Rogers 1984) and a desire to return to the pre-disaster city (Haas et. al. 1977). This is important, since planners and others involved in directing a community's recovery should be aware that the image most people hold for recovery is a return to what was.

There is a large information gap on the specific societal or psychological impacts of loss of infrastructure and lack of service from lifelines. Some economic analysis has taken place however. For example, after the Loma Prieta earthquake, part of what enabled businesses to recover quickly was a quick restoration of service and the redundancy built into many infrastructure systems (United Nations Center for Regional Development 1990). Lifeline repair is part of the early stage of emergency response.

The literature on societal impacts clearly indicates that different groups respond differently to earthquake damage. If we are to model societal impact, we must be able to identify the demographic groups that will be subject to different levels of damage. This model fills that role in the infrastructure area.

Repair

It is important to understand the current process of infrastructure repair in order to make meaningful recommendations about repair strategies. Essential lifelines are restored quickly since this repair must occur before recovery proceeds. Repair priorities are currently set using rules of thumb and the experience of system operators. There is little opportunity for analysis of repair priorities after a damaging earthquake. Any attempts to change repair strategies must occur prior to disasters and include the cooperation of owners, operators and regulators of the systems (Panel on Earthquake Loss estimation 1989).

Currently, water system repair follows an overall pattern of the least damaged lines fixed first. Seligson calculated time to repair as a function of number of breaks per square mile. Lines with few breaks and heavy demand are repaired first, and lines with many breaks and low demand are repaired last (Seligson 1990). The Applied Technology Council (1986) publishes a time-to-restore-service matrix for a variety of lifeline components. Attempts have already been made to computerize existing repair strategies (Iwata 1988). For the purposes of this research, it is a given that lifeline repair will occur and occur quickly, but the criteria of repairing the fastest repaired lines first may not be best. Differential impacts between various subpopulations should be considered and special attention should be paid to emergency facilities (Panel on Earthquake Loss Estimation 1989).

Based on our current understanding of societal impacts, methods of modelling physical damage, and current approaches to repair, it is possible to design a GIS-based system which combines sociological and technical knowledge. The common link is the demographic characteristics of the population. We can begin to understand the societal impacts of infrastructure damage if we can model the effects on different social groups, especially low income, the elderly and minority populations.

MODELING SOCIETAL IMPACTS

The modeling approach developed in this project characterizes societal impact in demographic terms. First round societal impacts are characterized as the number and type of population affected by infrastructure damage. The modeling is done within the Arc/Info Geographic Information System. As shown in Figure 1, the societal impact model consists of three modules: the simulation module, the assessment module and the repair module. All three modules were developed using Arc Macro Language (AML). A graphic user interface integrates the three modules and allows the system to be run by users with little or no GIS experience. The three modules are described in detail below.

Data Preparation

This GIS-based system requires digital information about the water distribution network, block-level census data, and information about earthquake intensity. In the GIS model, the water supply network consists of links and nodes. Each link represents a water pipeline that connects two adjacent nodes. Each node represents a pump station, a tank or a hydrant. For this initial implementation, we used the Memphis/Shelby County water distribution network digitized by the Earthquake Center at Memphis State University. A number of important attributes such as pipeline diameter and roughness are stored in the attribute database. Figure 2 shows the water distribution network.

The demographic information used in this analysis was drawn from the 1990 Census. It includes the population and number of housing units for each block (the smallest geographical area within the 1990 Census of Population and Housing). This information is provided on the Summary Table Format (STF-1B) CD-ROM and is stored in a series of dBASE databases from the US Census (U.S. Department of Commerce 1991). Population data were imported into an INFO database. Spatial information for the centroid of the block was stored in a spatial point database based on the latitude and longitude coordinates, and linked to the INFO database.

The information about earthquake intensity includes Peak Ground Acceleration (PGA) that measures the estimated ground motions for all locations in Shelby County. Given the data of water-supply network and the estimated PGA values, earthquake damage to the water-supply network can be calculated by the LIFELINE-W(I) system developed by the Civil Engineering Department of Princeton University (Tanaka et. al. 1993). Our GIS-based system can use the earthquake damage estimates directly from the LIFELINE-W(I) system, and combine them with the data on block-level population and housing units by using ARC/INFO spatial analysis tools.

One of the key technical challenges of this project was to find the most suitable way to link block level demographic data to the water distribution network. The population and housing information for each block is spatially related and aggregated to the corresponding nodes in the water system using the proximity features of the GIS system. This aggregation is crucial to the assessment of societal impacts of water-system damage and development of emergency response plans. The relating and aggregating process is shown in Figure 3 and can be described as follows:

- search the closest node for each centroid of block and assign the node number to the block. Adjust the search radius to a proper number so that all the centroids have their corresponding closest nodes. This search process is based on a reasonable assumption that all the people and housing units within a block area use water that is pumped out from the node closest to the centroid.

- aggregate (or sum up) the population and housing units of blocks with same node number and assign the results to the corresponding node. The results represent the total number of people and housing units that are served by the water distribution network through the node.

Demographic data is available at both the block and the block group level. Both of these data sets have their own strengths and weaknesses. At the block level the data is available for small areas of land that can be allocated to the centroids of the land areas. Fig. 3 shows this allocation as the "stars" located within each block. Using a spatial technique called a snapping, all the data at the centroids of the blocks are aggregated to the closest water network nodes (depicted by the heavy circles). Using the relatively small census blocks, nearly all of the nodes have data aggregated to them. The association of data to the majority of the nodes provides for more accurate analysis. The ratio of "nodes with data" to "total nodes" is called the snap ratio, and in our illustration it totals to 13/14.

More extensive demographic data is provided at the block group level (4-6 census blocks comprise each block group). Fig. 4 shows the same area, but at the block group level. The first marked difference is that there are fewer land areas, however they are much larger in comparison to Fig. 3. As in the first case, we snapped data from the centroids of the block groups to the closest nodes. It can be seen that there are fewer nodes with snapped data due to the relatively large size of the block group polygons. This causes limitations in the application of this GIS infrastructure model. The snap ratio as seen from Fig. 4 is 8/14.

It is clear that the block level provides a much better spatial resolution and congruence with the water network than does the block group. The better the snap ratio, the fewer the dataless water network nodes. Water network nodes with no information can be misleading, as we would assume that they would not affect any of the population. Thus a reduction in dataless nodes allows us to conduct a more comprehensive and comprehensible analysis.

At the block level the data is limited to a small number of variables. Table 1 shows the variables available at the block level, which are basic housing and population data. From this set of variables we are able to determine the effects to the various groups (white, black, under 18, over 65, etc.) and hence determine a strategy to optimize service.

Table 1. Population and Housing Variables of STF-1B	
Characteristic	Information within Characteristic
Persons	Total
Race	White Black American Indian, Eskimo or Aleut Asian or Pacific Islander
Persons of Hispanic Origin	Total
Age	Under 18 years 65 years and over
Housing Units and Units in Structure	Total 1 Unit Detached or Attached 10 or more units
Mean Number of Rooms	Mean number of rooms in the Housing Units
Tenure	Owner occupied housing units Renter occupied housing units
Mean Value	Mean Value for owner occupied housing units
Mean Contract Rent	Mean Contract Rent for renter occupied housing units
Housing units with 1.01 or more persons per room	Total occupied Renter occupied
Persons in occupied housing units	Total
Housing unit occupants	One person households Family householder, no spouse present with 1 or more persons under 18 present

The block group level provides a more extensive set of variables. There is more information on the breakdown of ages, the houses that utilize wells, sewage disposal and categorization of industry and its associated populations. This additional set of variables affords the opportunity to analyze the consequences of infrastructure damage on different groups in more detail. Table 2 shows the variables available at the block group level.

Table 2. Population and Housing Variables of STF-3A	
Characteristic	Information within Characteristic
Persons	Total
Race	White Black American Indian, Eskimo or Aleut Asian or Pacific Islander
Households	Total Families
Age	All ages Less than 10 Greater than 60
Group Quarters	Persons living in group quarters
Industry	Persons employed in various industries by SIC codes
Income	All household income Median Household Income
Water Source	Public water system Wells/other
Sewage Disposal	Public sewage disposal Septic tank or cesspool/other

Ideally, we would need to have data available at the block level in order to obtain a better snap ratio, and the multiplicity of variables presented at the block group level in order to obtain a broader spectrum of analysis.

Simulation Module

The system requires the user to run the simulation module first. This module generates the breaks that will be used in the later modules. It contains two methods for estimating earthquake damage to the water network. The first method requires the operator to select pipelines damaged by the earthquake. After the operator makes his or her selections, the system displays the location of the broken pipelines within the water network. This type of simulation is useful for directing emergency response. Immediately after the earthquake, the damaged pipelines can be located within the water network. Using the assessment and repair modules, the system estimates population no longer receiving water service and suggests an order of repair to restore service.

The second method directly incorporates output from a stand-alone damage model system. The LIFELINE-W(I) system estimates damage to water-supply networks under different conditions. Although this system primarily calculates the water flow under different damage conditions, it also generates pipeline damage data that can be used in our system for assessment of societal impacts, and for the generation of a repair strategy. In the LIFELINE-W(I) System, ground motions are considered the major cause of breaks in underground pipes, and are represented by two types of scenarios: uniform distributed ground motion and interpolated site-specific ground motion. The first scenario assumes the earthquake intensity is the same everywhere in the study area, and can be measured by the Modified Mercalli Intensity (MMI). The latter scenario assumes ground motion intensity varies from place to place, and it estimates the intensity at each location within the study area by spatially interpolating peak ground acceleration (PGA) from a set of sample PGA values. Using each of these two scenarios, the LIFELINE-W(I) system estimates the occurrence rates of pipeline failure and calculates water flows in terms of pressure and water head. The occurrence rates of pipeline failure are stored in an ARC/INFO database that our system can easily access.

Figure 5 is an example of a map produced by the simulation module. In this figure, the wide dotted links represent the pipelines broken by the earthquake, and the black stars represent the locations of pump stations (or tanks) within the water supply network.

Assessment Module

This module calculates the demographic impacts of the simulated breaks on the population. It uses the inputs produced by the simulation module to estimate population impacts of the damage. In effect, the broken pipelines designated in the simulation module divide the water-supply network into a number of separate subsystems. The assessment module evaluates the connectivity of these subsystems to the system as a whole. This module then estimates the societal impacts of the damage to the water-supply network in terms of population and housing units that are still served or no longer served by the water network after the earthquake. To do this, the system follows three major steps.

First it determines which pipelines within each subsystem are still connected to pump stations (or tanks) and which are no longer connected. The pipelines connected to the pump stations (or tanks) are assumed to remain in operation after the earthquake. The pipelines disconnected from the pump stations (or tanks) are considered out of service. The system then determines the size of the population and the number of housing units still served by each subsystem. It also calculates the size and number no longer served. The population and housing units that are served by pipelines still in operation are assumed to have water service. Conversely, those linked to dead pipelines are assumed to lack water service. Finally, the module summarizes, for the system as a whole, the size of the population and the number of houses that are still served by the water-supply network and the size and number no longer served.

There are two possible outputs from the assessment module. Figure 5 is an example of one type of map produced by this module. In this figure, the solid links represent the operative pipelines after the earthquake, the dotted links represent the dead (or out of service) pipelines, and the wide dotted links represent the broken pipelines. This map displays the total population and number of housing units no longer served by the system given that five pipelines -- 579, 591, 604, 610, and 812 -- are broken after an earthquake. The alternative display is much like Figure 5 except that this map shows the total population and housing units still served by the water network.

Repair Module

Developing a good emergency response plan immediately after an earthquake is a sophisticated optimization task. It usually involves a thorough understanding of characteristics of the damaged water supply network and the societal impacts of the damage. The repair module developed in this study generates a response plan based on the service population of each pipe. The information about the broken pipelines and their related population is provided by the simulation and assessment modules.

The system simulates the repair process by selecting one broken pipeline at a time, evaluating the connectivity of the water network if that pipeline is repaired, and estimating the number of people for whom service will be restored. The broken pipeline that restores service to the most people is given highest priority. The system then assumes this pipeline has been repaired, and continues the repair analysis for the remaining broken pipelines. When completed, the system displays a priority list of repair to restore service. Figure 7 shows a priority repair list for the damaged water-supply network. In this case, pipeline 591 should be repaired first, pipeline 604 second, pipeline 812 third, and so on.

CONCLUSION

The GIS-based system developed in this research utilizes a modular approach to analyze the societal impacts of earthquake damage to an urban infrastructure system, specifically a water-supply network. The interface of this system is designed so the operator does not need to have knowledge of ARC/INFO software.

To analyze the societal impacts of infrastructure damage and generate a reasonable emergency response plan, the system simulates earthquake damage to the water-supply network using one of three possible methods and combining the results with demographic information from the 1990 Census of Population and Housing.

In generating an emergency response plan, this system considers the characteristics of the damaged water-supply network, the societal cost of the damage, and the capacity and size of the repair team. However, it does not consider the difficulty of restoring a broken pipeline or the time required for the repair. This issue will be considered in later research. Also, the pump stations or tanks might be out of operation after an earthquake; the system should consider their societal losses in the future.

FUTURE RESEARCH

This project will build upon the earlier work to incorporate impacts on economic activities and critical facilities. To effectively estimate the economic impacts of infrastructure damage, it is first necessary to locate the various economic activities with enough precision to determine their relationship to the infrastructure network. The U.S. Census Bureau does not publish the results of its economic census for areas smaller than the place level. Therefore address matching of local records maintained for tax assessment and business licenses provides the best method of locating economic activity. Once located, economic activities can be associated with support infrastructure using the same basic techniques currently used for population. By making this link, we can identify those activities that will be without fire protection after an event. We can also identify those business and critical facilities that are likely to experience significant service interruption. This will allow interruption and input/out modeling efforts. These economic impacts can then be integrated and balanced with the social impacts currently produced by the model.

REFERENCES

Applied Technology Council. 1986. ATC-13: *Earthquake Damage Evaluation Data for California*. Federal Emergency Management Agency, Applied Technology Council, California.

Bolin, Robert. 1982. *Long-term Family Recovery from Disaster*. Monograph #36. Boulder, CO: University of Colorado.

Bolin, Robert. 1988. "Response to Natural Disaster," *Mental Health Response to Mass Emergencies*. New York: Brunner Mazel. p. 22-52.

Bolin, Robert. 1993. *Household and Community Recovery after Earthquakes*. Monograph #56. Boulder, CO: University of Colorado.

Committee on Earthquake Engineering Research. 1982. *Earthquake Engineering Research*. Commission on Engineering and Technical Systems, National Research Council. Washington: National Academy Press.

Emmi, Philip C. and Carl A. Horton. 1993. "A GIS-based Assessment of Earthquake Property Damage and Casualty Risk: Salt Lake City, Utah." *Earthquake Spectra*. V. 9, no. 1, p.11-27.

French, S.P. and Isaacson, M.S. 1984. "Applying Earthquake Risk Analysis Techniques to Land Use Planning." Journal of the American Planning Association.

Haas, J. Eugene, et al eds. 1977. *Reconstruction Following Disaster*. Cambridge: MIT Press.

Honegger, Douglas G. 1991." Gas System Repair Patterns in San Francisco Resulting from the 1989 Loma Prieta Earthquake." *Lifeline Earthquake Engineering" Proceedings of 3rd U.S. Conference*. August 22-23, 1991. Los Angeles: American Society of Civil Engineers. p. 1079-1088.

Hwang, H. and Huijie Lin. 1993. *GIS Database for Mapping Seismic Hazards and Seismic Risk in Memphis and Shelby County, Tennessee*. Center for Earthquake Research and Information, Memphis State University.

Iwata, Takashi and Hiroyuki Nakana. 1988. "Restoration Planning System for Earthquake Damaged City Gas Pipelines." *Proceedings of 9th World Conference on Earthquake Engineering*. August 2-9, Tokyo. V.7, p.171-176.

National Institute of Building Sciences. 1994. *Development of a Standardized Earthquake Loss Estimation Methodology, Vols. I and II.* Risk Management Software, Inc., California.

Olshansky, R. 1992. *Seismic Hazard Mitigation in the Central United States: The Role of the States.* U.S. Geologic Survey, Branch of Geologic Risk Assessment.

Panel on Earthquake Loss Estimation Methodology Committee on Earthquake Engineering. 1989. *Estimating Losses from Future Earthquake -- Panel Report.* Commission on Engineering and Technical Systems, National Research Council. Washington: National Academy Press.

Patel, Jigar. 1991. *Estimating Infrastructure Elements Using Geographic Information Systems.* Ithaca, NY. Cornell Institute for Social and Economic Research Program in Urban and Regional Studies.

Perkins, J.B. 1992. *Estimates of Uninhabitable Dwelling Units in Future Earthquakes Affecting the San Francisco Bay Region.* Oakland, CA: Association of Bay Area Governments.

Pezeshk, S. et al. 1993. "Seismic Vulnerability Evaluation of Bridges in Memphis and Shelby County, Tennessee." *Earthquake Spectra.* V.9, no.4, p. 803-815.

Rebuilding After Earthquakes: Lessons From Planners. 1991. Portola Valley, CA: William Spangle & Associates.

Risk Management Software, Inc. and California Universities for Research in Earthquake Engineering. 1994. <u>Assessment of the State of the Art Earthquake Loss Estimation Methodologies</u>. (FEMA-249). Jessup, MD: Federal Emergency Management Agency.

Rogers, George Oliver and Jiri Nehnevajsa. 1984. *Behavior and Attitudes Under Crisis Conditions: Selected Issues and Findings.* Pittsburgh: University of Pittsburgh.

Sato, R. and M. Shinozuka. 1991. "GIS-based Interactive and Graphic Computer System to Evaluate Seismic Risks on Water Delivery Networks." *Lifeline Earthquake Engineering: Proceedings of 3rd U.S. Conference.* August 22-23, 1991. Los Angeles: American Society of Civil Engineers. p. 651-660.

Scawthorne, Charles. 1986. "Rapid Assessment of Seismic Vulnerability." *Techniques for Rapid Assessment of Seismic Vulnerability.* New York: American Society of Civil Engineers.

Seligson, H.A. et al. 1990 " Comparison of Lifeline Response and Recovery Performance in the 1971 San Fernando and 1987 Whittier Narrows Earthquake." *Proceedings of Fourth U.S. National Conference on Earthquake Engineering*. May 20-24. V.1, p. 895-904.

Shah, Haresh and J. R. Benjamin. 1977. "Lifeline Seismic Criteria and Risk: A State of the Art Report." *The Current State of Knowledge of Lifeline Earthquake Engineering*. New York: American Society of Civil Engineers.

Shinozuka, M., H. Hwang and M. Murata. 1992. "Impact on Water Supply of a Seismically Damaged Water Delivery System." *Lifeline Earthquake Engineering in the Central and Eastern U.S.*, ed. D.B. Ballantyne, Monograph No. 5, Technical Council on Lifeline Earthquake Engineering, ASCE, New York.

Shinozuka, M. , M. Murata, and H. Hwang. 1993. *Restoration Planning for Memphis Water Delivery Network Based on Simulated Seismic Damage*. National Earthquake Conference.

Tanaka, S. et al. 1993. "LIFELINE-W(I) USERS' GUIDE -- GIS Application For a Water Delivery System Under Intact and Seismically Damaged Conditions." Technical Report NCEER-93-xxxx.

Tobin, G.A. and J.C. Ollenburger. 1992. "National Hazards and the Elderly." Quick Response Research Report #53; Boulder, CO: University of Colorado.

Tubbesing, S.K. 1992 " Lessons Learned in the Post-Earthquake Investigation Process." *Earthquake Engineering Tenth World Conference*. Rotterdam: Balkena. p. 6117-6120.

United Nations Center for Regional Development. 1990 *The Socioeconomic Impacts of Disasters*. Nagoya, Japan: United Nations Center for Regional Development.

United States Department of Commerce. 1991. *1990 Census of Population and Housing: Summary Tape File 1B Extract on CD-ROM, Technical Documentation*. Washington: Department of Commerce.

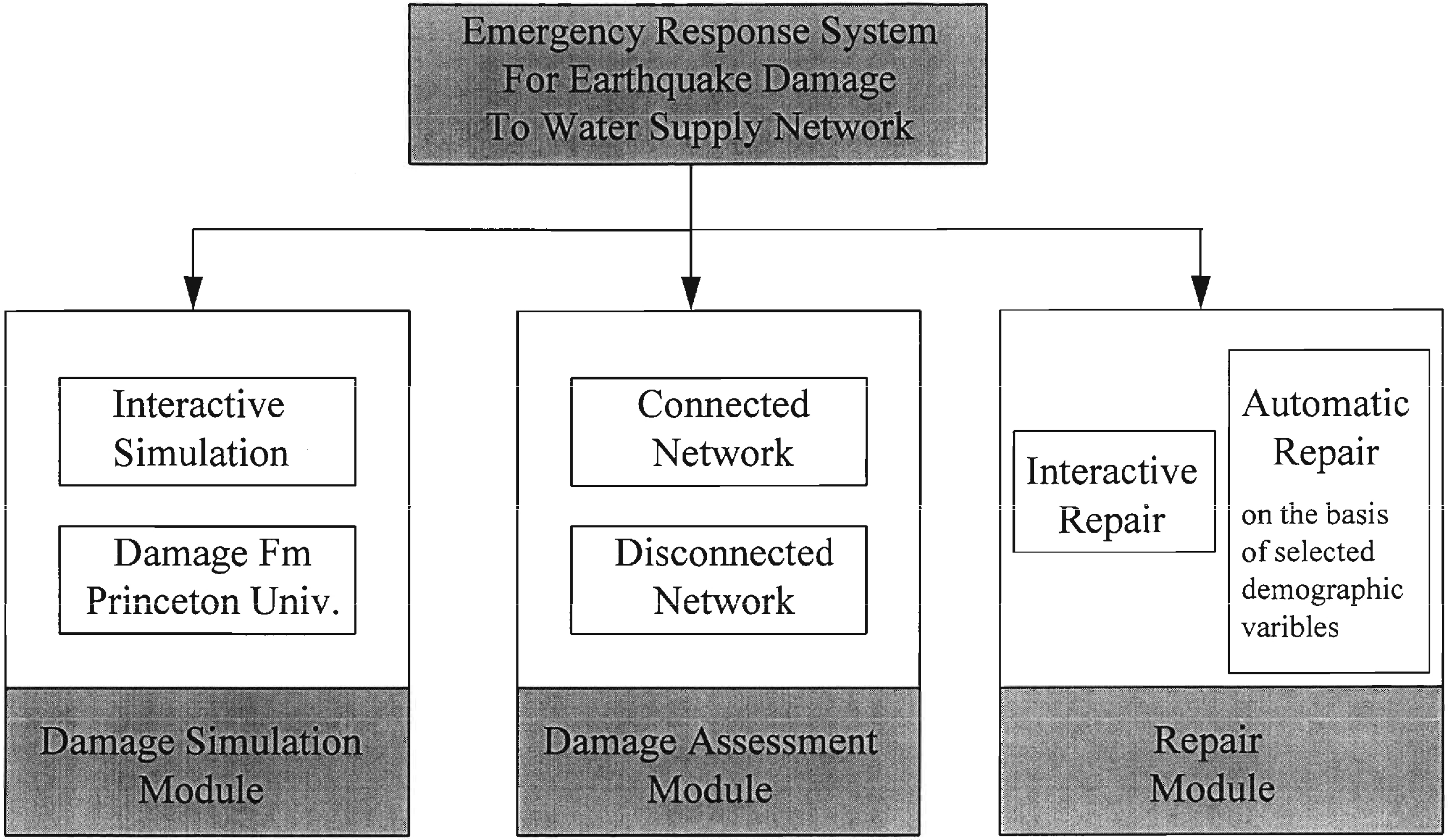


Figure 1 Conceptual Framework of the GIS Based Emergency Response System

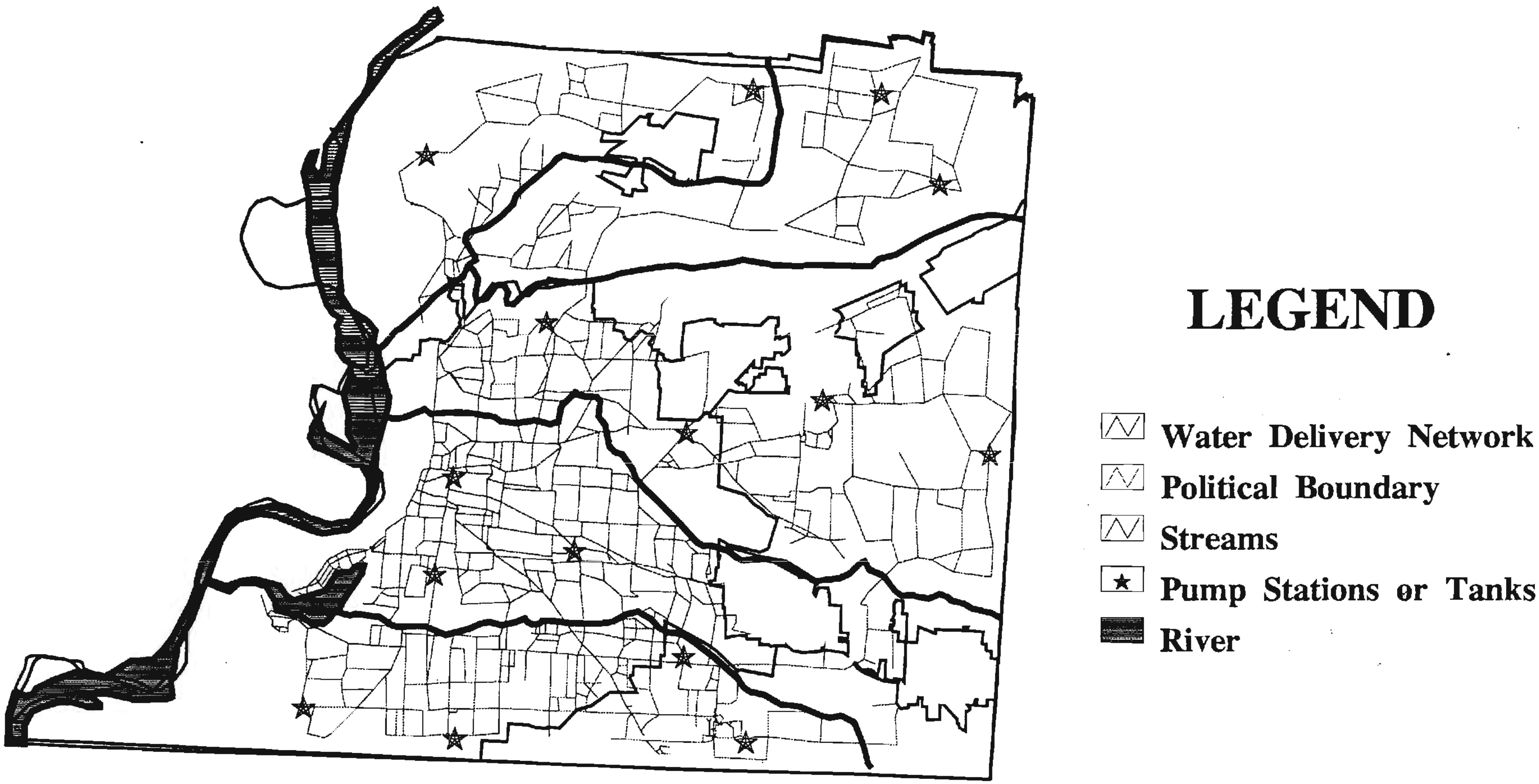
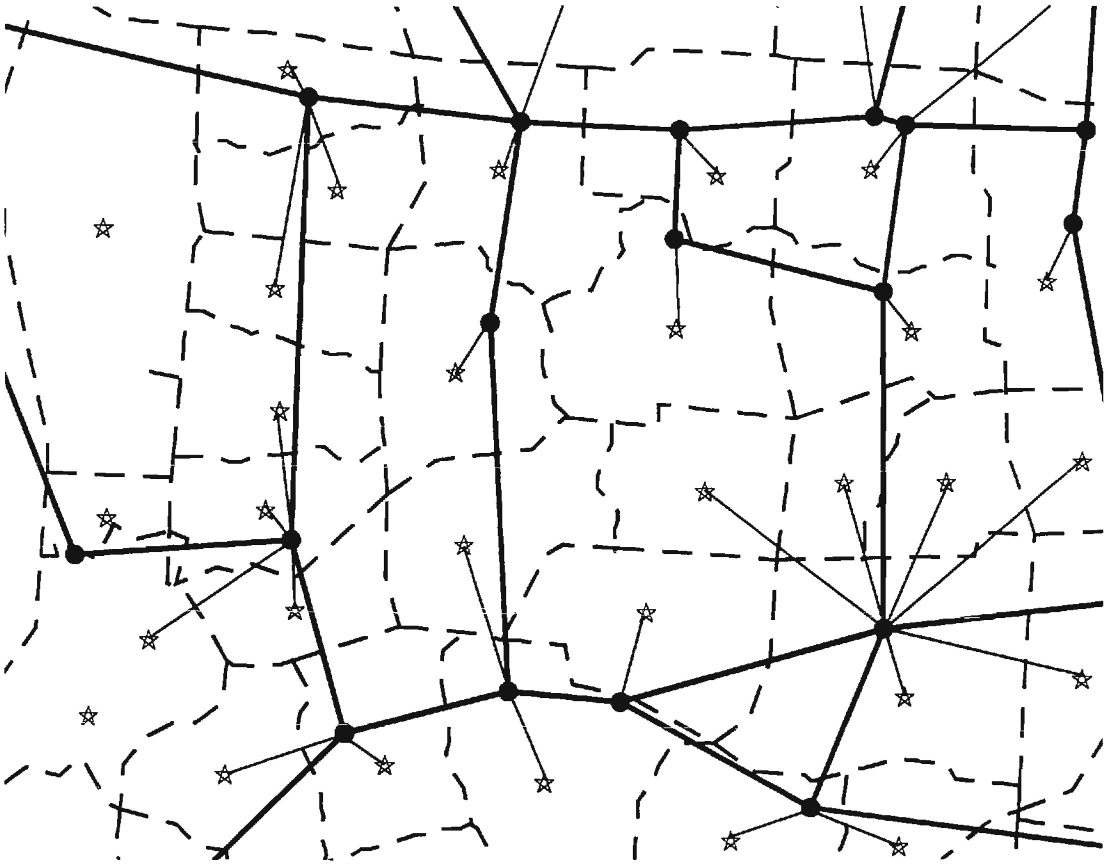


Figure 2 Water Network in Shelby County, Tennessee



Point-to-Node Aggregation

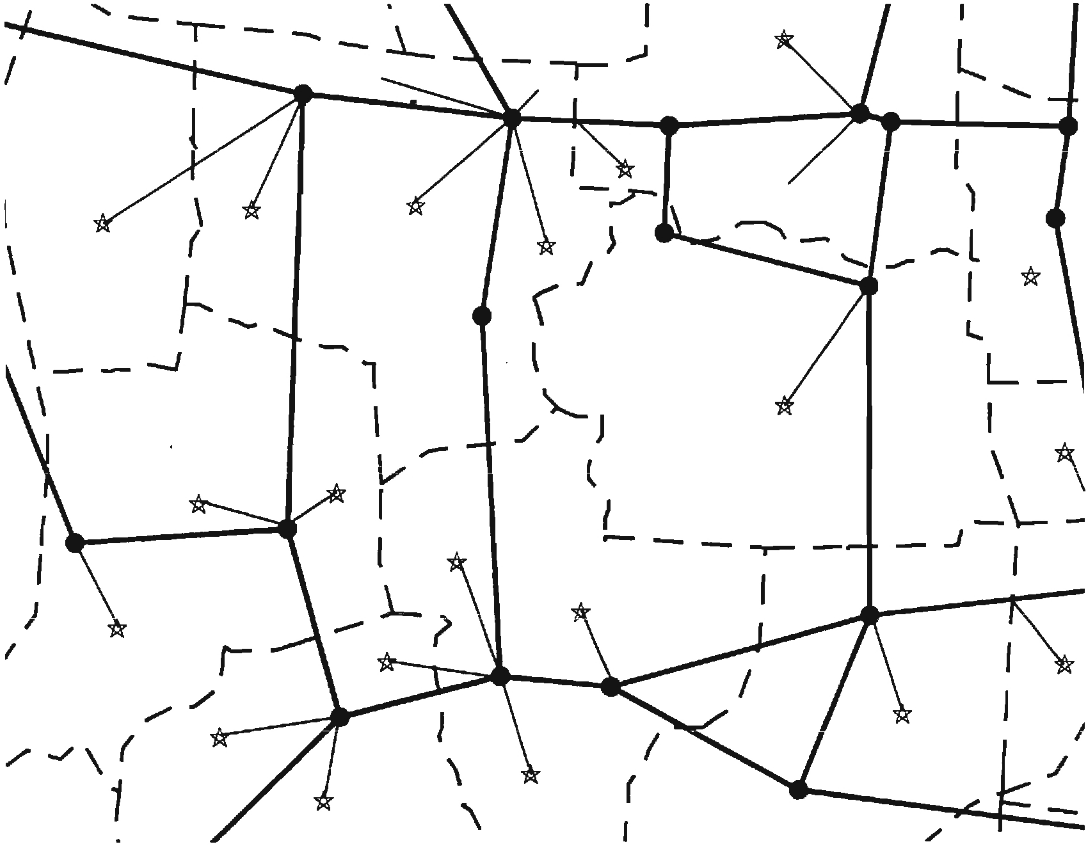
$$\text{PopNode} = \sum_{i=1}^{j} \text{Pop of Block Centroids}$$

where j is the total no. of block centroids within close approximity of a node.

LEGEND

- Water Delivery Network
- Block Boundary
- Connectors
- Network Nodes
- Block Centroids

Figure 3 Aggregation of Block Centroid Population to Water Network Nodes



Point-to-Node Aggregation

$$\text{PopNode} = \sum_{i=1}^{j} \text{Pop of Blockgroup Centroids}$$

where j is the total no. of blockgroup centroids within close approximity of a node.

LEGEND

- Water Delivery Network
- Blockgroup Boundary
- Connectors
- Network Nodes
- Blockgroup Centroids

Figure 4 Aggregation of Blockgroup Centroid Population to Water Network Nodes

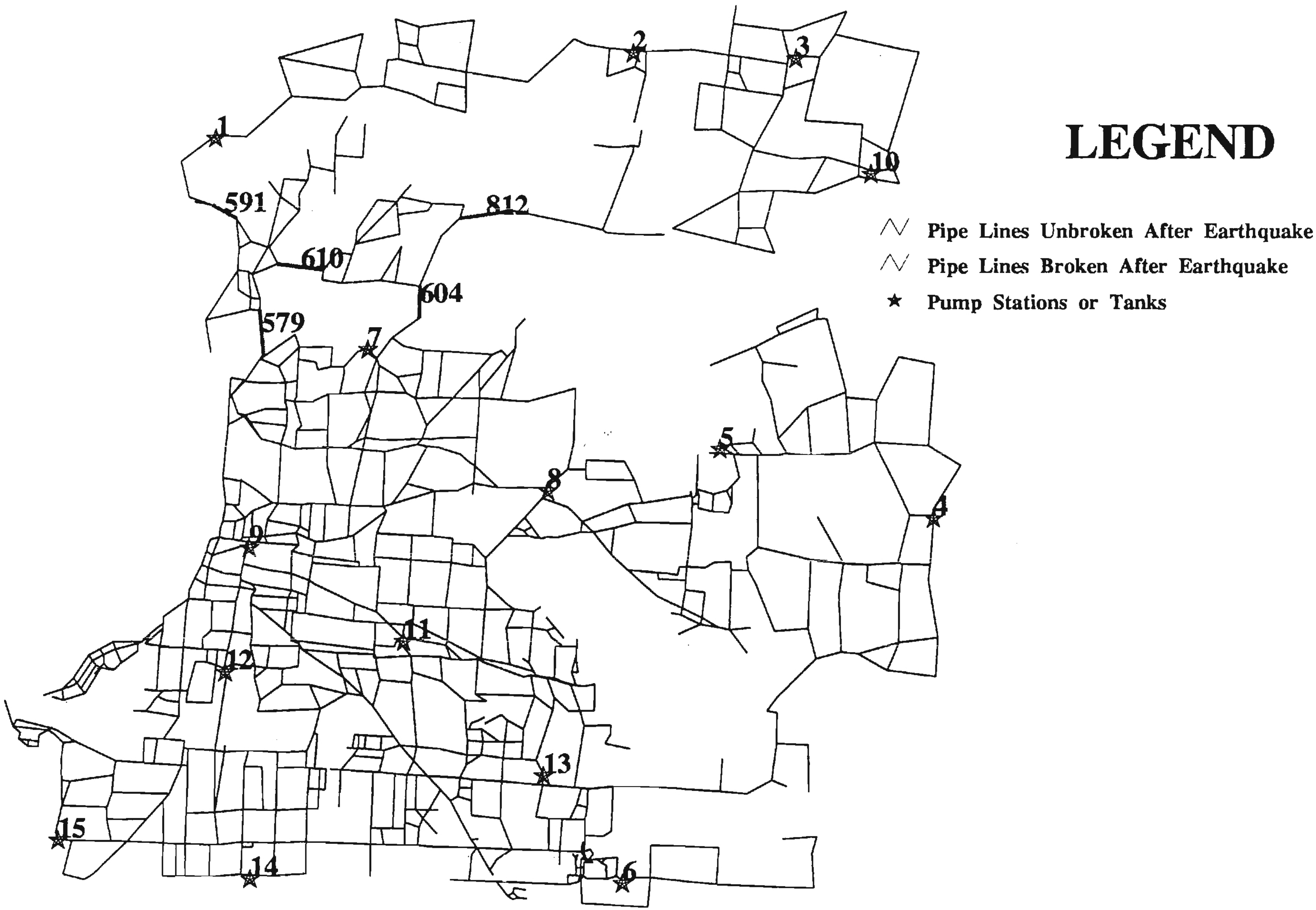


Figure 5 Simulation Results Generated By The Earthquake Damage Module

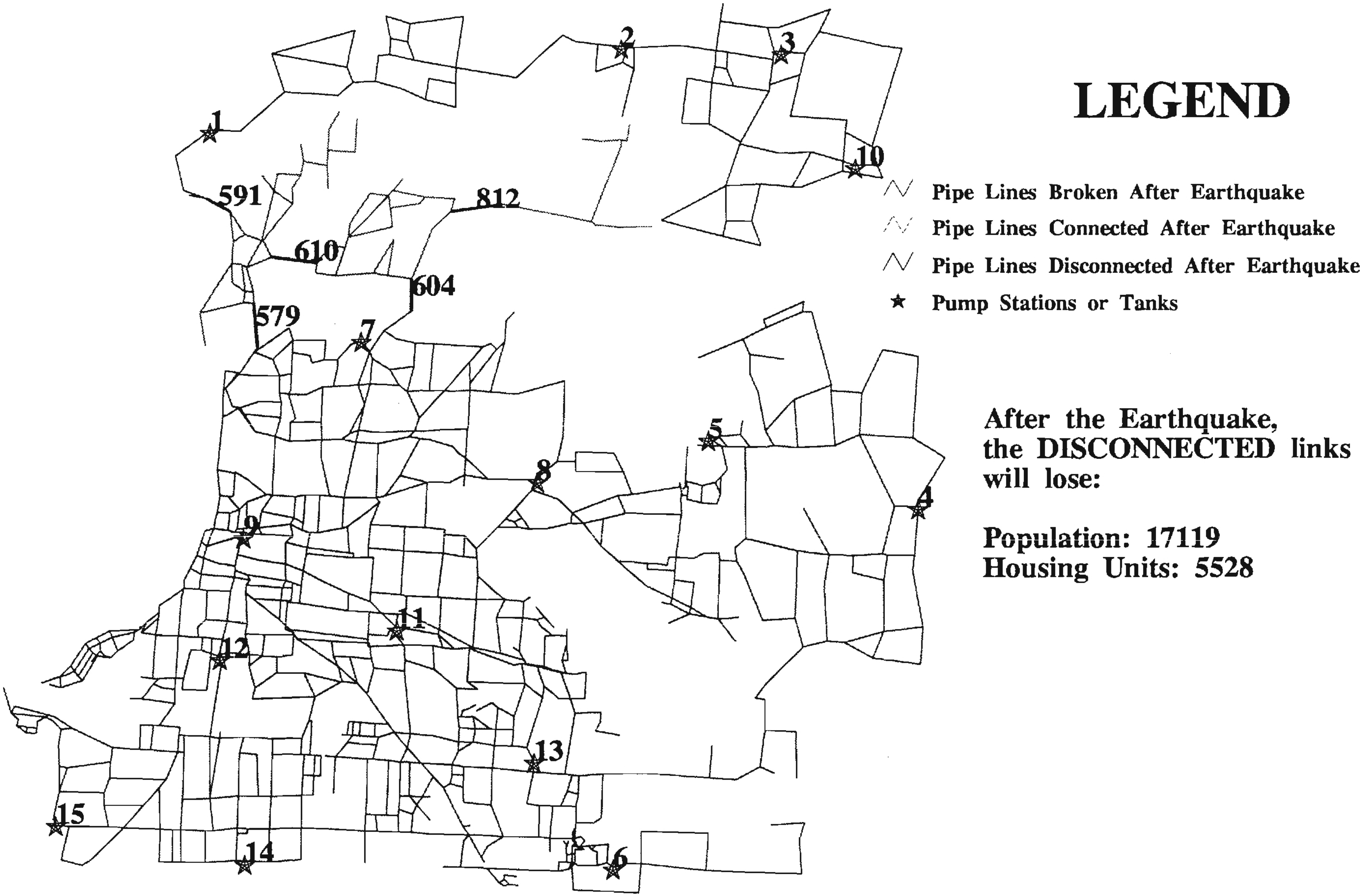
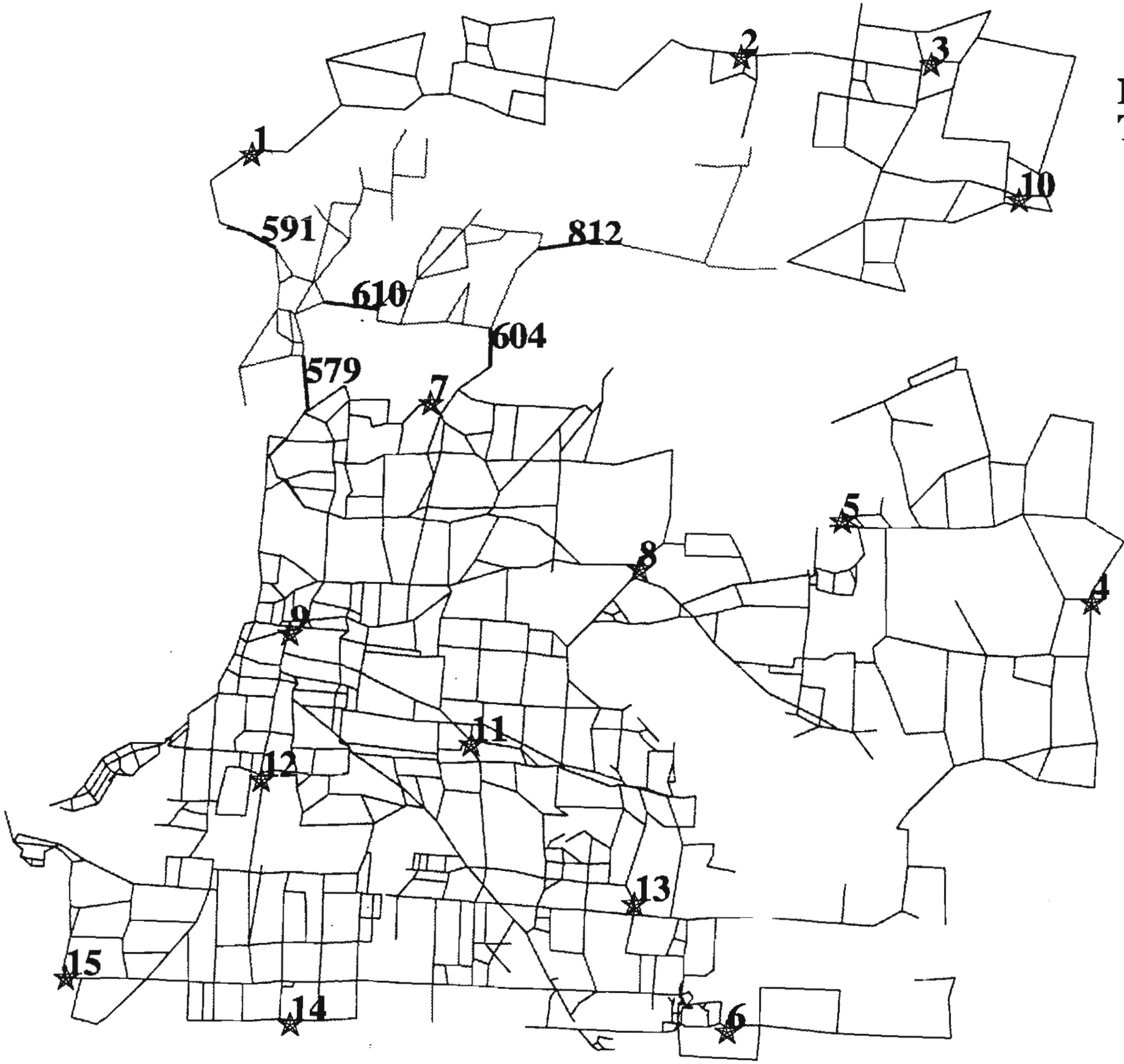


Figure 6 Population and Housing Units Lost Service After The Earthquake



PRIORITY LIST FOR REPAIRING THE BROKEN PIPELINES:

ORDER	LINK-ID	RESTORED-POP	RESTORED-HU
1	591	6311	2028
2	604	4703	1622
3	812	6104	1877
4	579	1	1
5	610	0	0

Figure 7 A Priority List of Repairing the Broken Pipelines

D-48-A86 #3

City Planning Program
College of Architecture

Estimating Societal Impacts of Infrastructure Damage with GIS

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Final Report to National Center for Earthquake Engineering Research

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January 1996

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INTRODUCTION

Current earthquake infrastructure damage models typically produce damage estimates that are expressed in terms of physical damages. For example, for the water distribution systems the Applied Technology Council approach produces estimates of the number of breaks per kilometer (Applied Technology Council, 1985). While this type of damage estimate represents a large step forward in understanding the impact of an earthquake on infrastructure systems, it does not fully meet the needs of emergency preparedness and hazard mitigation planners. What is needed is a way to translate this physical damage into its resultant impact on society. The purpose of this research project is to develop techniques for estimating the size and characteristics of population impacted by earthquake damage to urban infrastructure systems. Such demographic data is the first step toward a complete understanding of the full dimension of societal impacts. The type of damage information will help decision makers allocate emergency response resources in the most effective manner and set priorities for hazard mitigation efforts.

Most state-of-the-art infrastructure damage models use geographic information systems (GIS) to estimate earthquake damage.[1] The GIS provides a number of features that are important to the damage process. Since infrastructure systems are spread over fairly wide areas that include a variety of surficial geology conditions, the geographic information system's ability to store and manipulate large amounts of spatially distributed information is helpful. The GIS uses a relational database to store attribute information that describes the characteristics of system components that are important in determining their response to ground shaking and other earthquake-induced effects. It also provides the spatial analysis tools needed to combine geotechnical information with system characteristics based on location. Typically, this type of modeling produces an estimate of the number of physical breaks in the system or an estimate of direct costs associated with repair of the system. Existing models do not consider the service population associated with various parts of the system.

This research project developed a GIS-based system (called PIPELINE-FIX) designed to link components of the physical system (e.g. individual water lines or pump stations) to small area population and economic data. PIPELINE-FIX associates demographic information from the 1990 Census of Population and Housing with nodes on the water distribution network. It can then estimate the number and characteristics of people impacted by infrastructure damage at various locations based on the topological relationships of the distribution network. Once we know the number and characteristics of the effected population, we are better able to understand the societal impacts of the damage to the system. PIPELINE-FIX then develops a repair strategy based on user-selected demographic characteristics. Thus, this system moves from physical measures of damage to societal impacts defined by the size and type of population being served.

PIPELINE-FIX provides the user with several alternative ways to determine the damaged condition of the water system network. The user may indicate the links that have been

[1] For an excellent review of damage modeling techniques, see Risk Management Software and California Universities for Research in Earthquake Engineering, 1994.

damaged interactively. This mode will be most useful in a real-time application in a post earthquake situation. The system can also accept a damage scenario generated by a separate water system damage model. In this prototype application we have linked PIPELINE-FIX to the LIFELINE-W(I) model developed by Shinozuka and his associates for the Memphis metropolitan area (Shelby County). The model has been developed in such a way that it should be possible to link it to other damage models, if desired.

To support real-time system repair or to prioritize earthquake mitigation expenditures, the societal impact model includes an optimization routine that rank-orders the pipe segments to be repaired or strengthened based on the service population of each segment. This allows an emergency manager or hazard mitigation planner to identify those pipe segments that are most important in terms of their societal impact. The system such allows the user to focus not only on the size of the service population, but also on population characteristics as age, income or ethnicity. For example, the system can identify those segments that serve the maximum number of elderly people. Thus, the system can inform decision makers on the characteristics of users subject to service interruption and allows them to develop or mitigation strategies that minimize the impacts on particularly vulnerable segments of the population.

This report contains four sections in addition to this *Introduction*. Section 2, *Literature Review*, summarizes key research in the methodologies and techniques for lifeline damage modeling. It also examines key research on the societal impacts of earthquakes and other natural disasters. The review presents the foundations of this research from a variety of disciplines and develops the approach used for modeling social impacts. Section 3, *Modeling Social Impacts,* discusses the development of the GIS-based system for estimating the societal impacts. It describes the data used to support the system and the spatial analysis techniques used to link demographic characteristics to the infrastructure system. Section 4, *Sensitivity Analysis*, explores the sensitivity of the system output to the selection of particular demographic characteristics as measures of societal impacts. It also tests the results obtained from using two different levels of spatial aggregation for the demographic data - census blocks versus census block groups. Section 5, *Conclusion and Future Research*, summarizes the research results and highlights issues related to further development of this modeling approach.

LITERATURE REVIEW

Urban infrastructure systems that are susceptible to damage by earthquakes are often referred to as lifelines. Lifelines, including water and sewer systems, electric power lines and telephone systems, are crucial to supporting human activities. Damage to lifelines after an earthquake, flood, or other natural disaster has physical, social, economic and technological impacts. Over the past twenty years there has been a significant amount of research directed toward developing methodologies to estimate the lifeline damage likely to occur after an earthquake or other natural disasters.

Most early damage studies focused on the building stock and paid little attention to infrastructure systems. The classic work by Algermissen et. al (1978) is typical of these early studies that classify the building inventory into a number of categories and apply separate loss functions to each category. In the early 1980's lifelines began to get more attention. A pair of studies by the California Division of Mines and Geology (Davis et al., 1982a; Davis et al., 1982b) considered the infrastructure damage of a magnitude 8.3 event on the San Andreas fault in Los Angeles or the San Francisco Bay Area.. These studies used manual mapping techniques and expert opinion to estimate the likely service interruption impacts resulting from a major scenario earthquake.

In ATC-13 the Applied Technology Council (1985) developed a comprehensive methodology for estimating damage from earthquakes. This approach used expert opinion to develop damage probability matrices for 80 classes of buildings and infrastructure components. For linear facilities, such as pipelines, the matrices expressed the likelihood of experiencing a given number of breaks per kilometer for earthquakes of Modified Mercalli Intensities from VI through XII. Network connections between system components were not explicitly treated, therefore each component was considered independently. The method was extended to include estimated restoration times in ATC-25 (Applied Technology Council, 1991).

In the late 1980's there was increased research on the performance of individual infrastructure components, particularly water and natural gas pipelines (O'Rourke, 1989). Component level studies of water system performance were undertaken by O'Rourke (1991) and others. Thus, we see the state of knowledge regarding infrastructure system performance increasing rapidly during the 1980's with increased attention to component level analysis.

In the mid-1980's geographic information systems began to be used to estimate damage to building stocks (French and Isaacson, 1984). It was not long before the advantages of the GIS damage modeling approach began to be applied to infrastructure systems. O'Rourke (1989) developed a program entitled GISALLE to estimate the reliability of water delivery systems. Sato and Shinozuka (1991) developed a GIS-based model for the Memphis area water distribution system. The standardized loss estimation methodology currently being developed for the Federal Emergency Management Agency by the National Institute of Building Sciences (1994) uses a GIS to combine seismic hazard and inventory information at the census tract level. A GIS provides a way to integrate knowledge about the causes of physical damage with characteristics of the distribution network to estimate both system damage and performance.

While large strides have been made in our ability to model earthquake damage, this technical work has remained largely separate from the research on societal impacts of earthquakes and other natural hazards (Tubbesing 1992). In part this separation may be the result of the information gap on the specific societal impacts of infrastructure damage and the loss of service from lifelines. Currently, the lifeline infrastructure research is expanding to include the social and economic impacts of disasters and the process of recovery from them.

The short term social impacts of an earthquake include the need for food, water, shelter, medical and psychological services. Haas et al., (1977) identified social networks as important components in supporting the recovery process. It is now widely recognized that earthquake damage differentially impacts various age, income and ethnic groups. These impacts are caused not only by direct damage, but also by interruption of important lifeline services. The National Academy of Sciences (Panel on Earthquake Loss Estimation, 1989) suggests that these differential sub-population impacts should be considered in emergency planning and response. Rubin and Palm (1987) have documented that immigrant populations were disproportionately impacted by the Whittier Narrows earthquake. Bolin (1993) found that Hispanic victims were less likely to relocate after the Loma Prieta earthquake, even if there homes were heavily damaged. Greene and Shulz (1993) found that the emergency shelter and replacement housing impacts of the Loma Prieta earthquake disproportionately impacted low income residents. Bolin also found there was a shortage of housing available for low income residents after the earthquake.

The social impacts of disasters on the elderly have also received considerable attention. Bolin (1982) discovered that the elderly recover quickly from the initial emotional impact relative to other age groups, but they experience a substantial decline in their standard of living. Researchers differ on whether the elderly experience disproportional impacts from disasters.

The separation of social and economic impacts from physical damage estimates affects the determination of repair strategies. The current process of infrastructure repair can be characterized as one in which the least damaged lines are fixed first. Seligson (1990) has calculated time to repair as a function of number of breaks per square mile. Lines with few breaks and heavy demand are usually repaired first, and lines with many breaks and low demand are repaired last. Several attempts have already been made to computerize existing repair strategies (Iwata, 1988), but these methods generally do not take societal impacts into account. For the purpose of this research, it is a given that lifeline repair will occur and occur quickly, but the criteria of repairing the fastest repaired lines first may not be best.

Based on our current understanding of societal impacts, methods of modeling physical damage, and current approaches to repair, it is desirable to develop a model that combines social and technical knowledge. The common link between these various elements is the demographic characteristics of the service population. If we can develop a model that estimates how infrastructure damage affects different social groups, especially low income, the elderly and the particular ethnic groups, we can begin to understand the societal impacts of infrastructure damage. The model developed in this research will attempt to make this connection.

MODELING SOCIETAL IMPACTS

The modeling approach developed in this project characterizes societal impacts in demographic terms. The basic premise is that societal impacts are a function of the number and type of population and housing that are affected by infrastructure damage. The modeling is done within the ARC/INFO Geographic Information System. As shown in Figure 1, the societal impact modeling system, PIPELINE-FIX, consists of three basic modules: the damage simulation module, the assessment module and the repair priority module. All three modules were developed using Arc Macro Language (AML). A graphic user interface integrates the three modules and allows the system to be run by users with little or no GIS experience. This section discusses the development of the PIPELINE-FIX system in terms of data preparation and the operation of the three major modules.

Data Requirements

The PIPELINE-FIX system requires information about the water supply network, demographic data, and information about earthquake impacts over the affected study area. The water supply network is often considered the most critical lifeline system because it supports many essential human needs. A functioning water distribution system is also necessary to fight fires following the earthquake.

The water supply network can be characterized as a series of links and nodes. Each link represents a water pipeline that connects two adjacent nodes. Each node represents an intersection of two or more pipe segments. Other components of the system, such as valves, pump stations and storage tanks are also represented as nodes on the network. The demographic data are the basic measurements of societal activities. In this system, the demographic data provide variables for estimating societal impacts of the water supply system damaged by an earthquake. In addition to the importance of the demographic data and the information about the water supply network, the earthquake intensity gives the measurement of the magnitude of the earthquake. In this system, it provides earthquake damage scenarios of the water supply network.

Our approach to estimating social impacts is based on understanding the characteristics of the population served by any particular link in the network. We have drawn a variety of demographic data from the 1990 Census of Population and Housing. This data is not available for individual households for privacy reasons, but is aggregated for small geographic areas. In this project we have used the two smallest units of aggregation - the census block and the census block group. Demographic data from these area features was then associated with the components of the water distribution network.

Study Area and Data Sources

Shelby County, Tennessee, which has nine cities including the city of Memphis, was selected as the study area for this project. Shelby County faces a significant earthquake hazard due to its

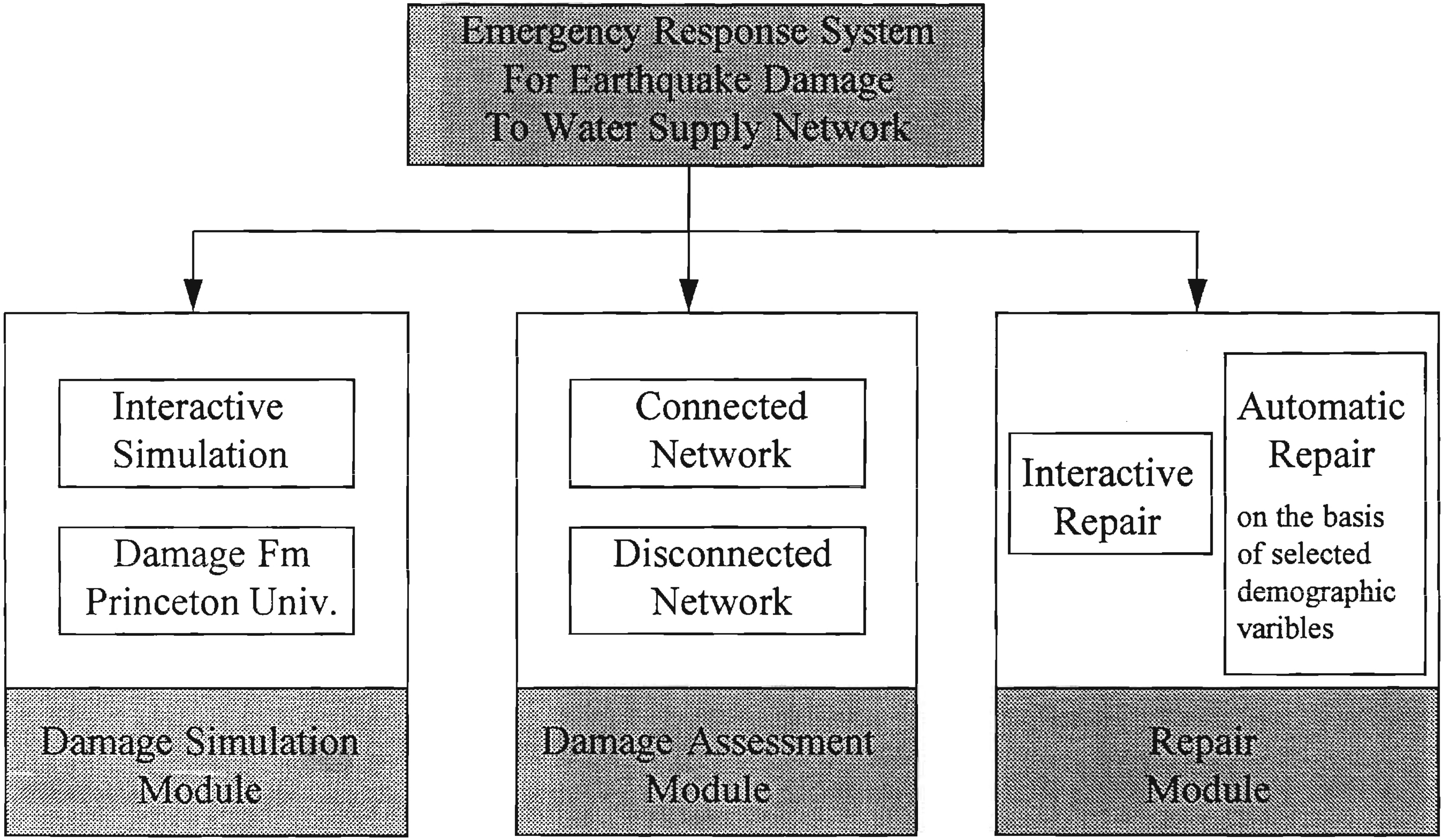


Figure 1. Conceptual Framework of the PIPELINE-FIX System

location in the New Madrid seismic zone. The selection of Shelby County also allowed this project to be integrated with ongoing work of other NCEER researchers.

Digital information related to the county, including information about the water distribution network, the population and housing stock and various real and simulated intensities of earthquake, are used in this system. The water distribution network was originally digitized by the Memphis State University. It is represented as a network coverage in the ARC/INFO geographic information system. A number of important characteristics of the components of the water system, such as pipeline diameter and roughness, are also stored in the ARC/INFO attribute database. Figure 2 shows the digitized water distribution network. The network contains 971 nodes, 1321 pipeline segments, and 15 pump stations and water tanks.

Coverages that describe Peak Ground Acceleration (PGA) and Modified Mercalli Intensity (MMI) for selected earthquakes are stored in the system. This model does not directly model physical damage to the infrastructure, but is linked to other models that perform this function. Currently, PIPELINE-FIX relies on damage scenarios generated by the LIFELINE-W(I) model developed by NCEER researchers at the Civil Engineering Department of Princeton University (Tanaka et al, 1993). PIPELINE-FIX also allows the user to interactively designate damage to the system without relying on a simulation model.

The demographic information used in the project was drawn from the 1990 Census of Population and Housing. The model uses various categories of data about population and housing available at the block and block group levels of aggregation. A block is a smallest geographical area defined for data reporting in the 1990 Census. Each block is a small area bounded on all sides by visible features such as streets, roads, streams, and railroad tracks or invisible boundaries such as city, town, township and county limits. In urban areas it is typically one city block. Figure 3 shows the blocks for Shelby County, Tennessee. Each block record in the database has a unique identification number and coordinates of its centroid assigned to it. These coordinates can be used to locate the centroids of the blocks within the county.

The block-level information was drawn from the Summary Tape File (STF-1B) CD-ROM published by the U.S. Census Bureau (U.S. Department of Commerce, 1991). Table 1 shows the major variables of STF-1B that are used in the project. The data collected at the block level are derived from a limited number of basic questions asked by the Census Bureau of the entire population and about every housing unit (also known as the short form). Probably the greatest weakness of the block level data is that it does not include any information about income or educational attainment. Median value of homes and contract rent can be used as surrogates for income, but are obviously imperfect substitutes. Similarly, the data on age and ethnicity does not provide much detail at the block level. The block level is, however, appealing because it is at a fine geographic grain. This is important in linking the data to the water network, which is also geographically detailed.

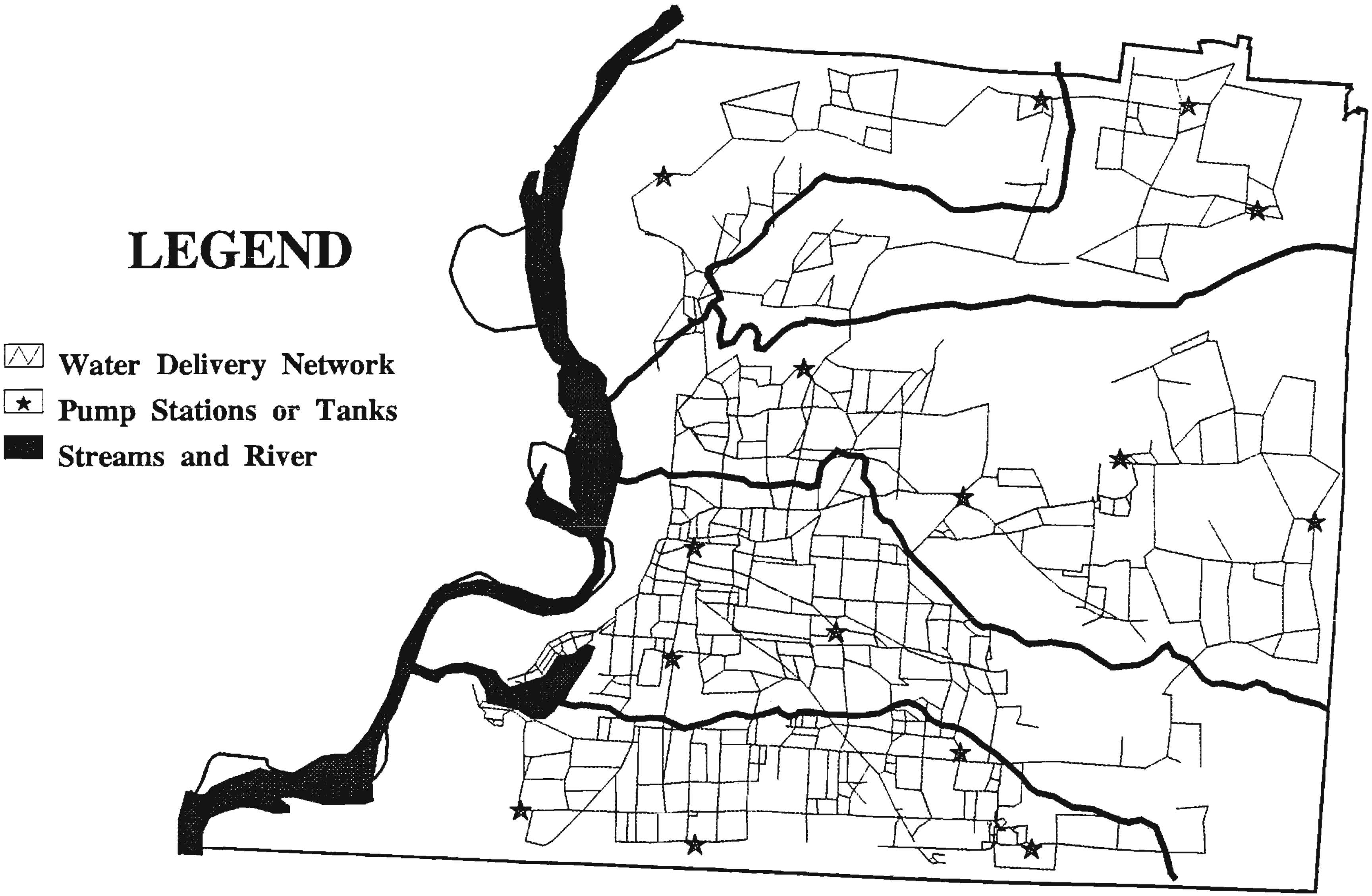


Figure 2. Water Network in Shelby County, Tennessee

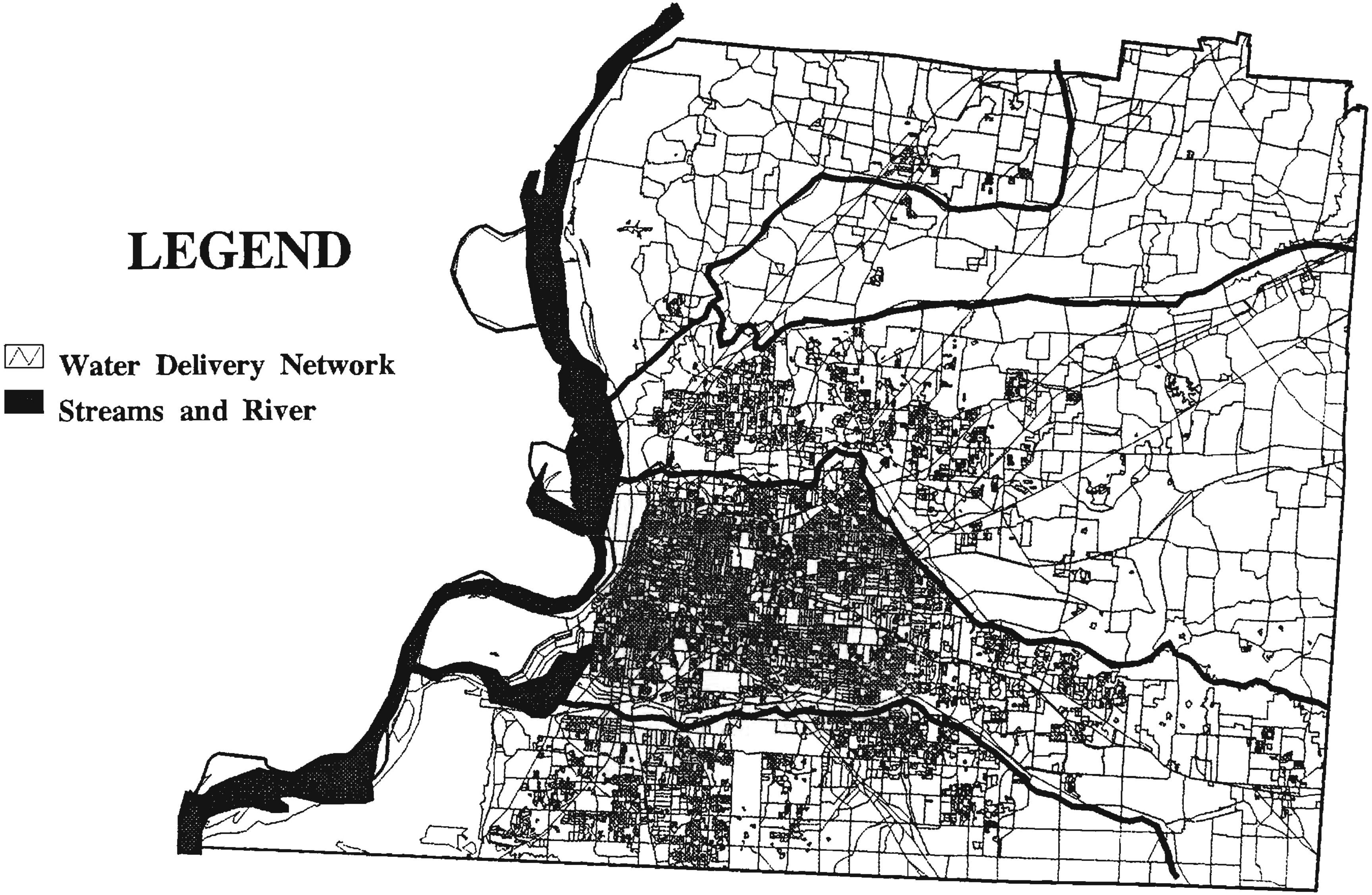


Figure 3. Blocks in Shelby County

Table 1. Variables at the Block Level (STF - 3B)

Characteristics	Information within Characteristics
Persons	Total
Race	White Black American Indian, Eskimo or Aleut Asian or Pacific Islander
Persons of Hispanic Origin	Total
Age	Under 18 years 65 years and over
Housing Units and Units in Structure	Total 1 Unit Detached or Attached 10 or more units
Mean Number of Rooms	Average Number of Rooms per Household
Tenure	Owner Occupied Housing Units Renter Occupied Housing Units
Mean Value	Average Sales Price
Mean Contract Rent	Average Rental Value
Housing Units with 1.01 or more Persons per Room	Total Occupied Renter Occupied
Persons in Occupied Housing Units	Total
Housing Unit Occupants	One Person Households Family Householder, no Spouse Present with 1 or more Persons under 18 Present

The Census Bureau publishes a richer set of data at the block group level. A block group is a collection of individual blocks, typically 8 to 12 census blocks containing 250-500 housing units. As with the blocks, each block group also has a unique identification number and the coordinates of its centroid assigned to it. Figure 4 shows the block groups in Shelby County. As indicated in the figure, there are 811 block groups.

The block group information is available on the Summary Tape File (STF-3A) CD-ROM the U.S. Census Bureau (U.S. Department of Commerce, 1991). Table 2 highlights the block group level variables used in the project. The data at the block group level are derived from a more detailed census questionnaire that is administered to a 1 in 6 sample of the population. The data include not only the population and housing counts available at the block level, but also information about education, occupation, income and more detailed categories of age and ethnicity. More detail is also available on the housing stock. Some of this, such as the amount of group housing (e.g. nursing homes) and source of water supply (e.g. private wells versus the public system) may be important in determining societal impacts. The key problem is that this richer set of data is only available for much coarser geographic areas.

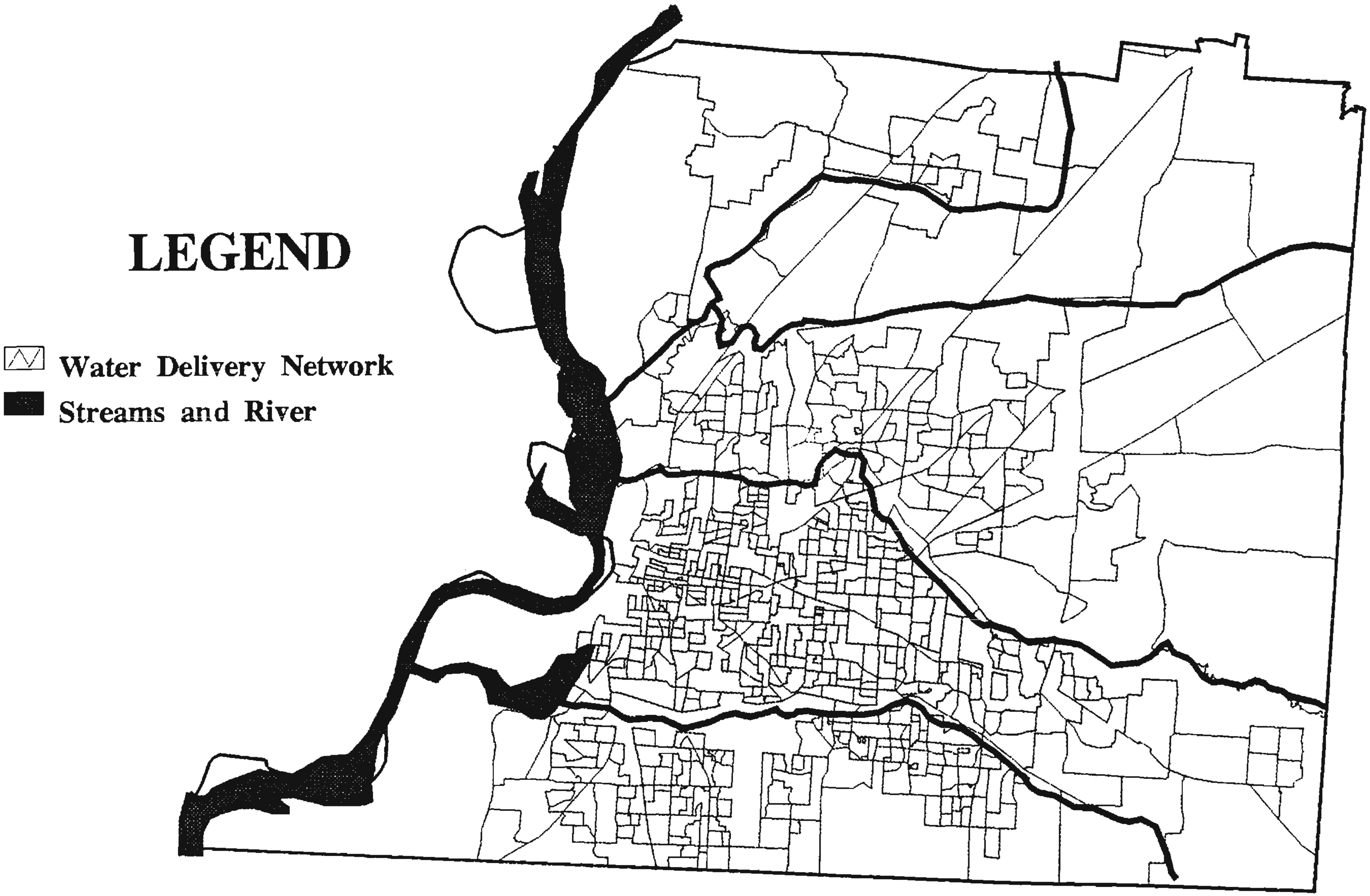


Figure 4. Block Groups in Shelby County

Table 2. Variables at the Block Group Level (STF - 3A)

Characteristic	Information within Characteristic
Persons	Total
Race	White Black American Indian, Eskimo Asian or Pacific Islander
Households	Total Families
Age	All ages Less than 10 Less than 18 Less than 60
Housing Units	Total Group Housing
Occupation	SIC Classifications
Income	Various Income Groups Poverty Status All Household Income Median Household Income
Water Supply	Public Supply Well
Sewage Disposal	Public Sewage Disposal Septic Tank or Cesspool/other
Structure	Median Building Age

The model developed in this project uses both of the above data sets to estimate the societal impacts of earthquake damages to the water supply network. Each data set has its own strengths and weaknesses. The data set at the block level has a small number of variables. Using this set of variables, the model can determine the impact of an earthquake on the overall population and on various broad social groups (white, black, under 18, over 65). The block group level provides a more extensive set of variables. There is more information on the breakdown of ages, the houses that utilize wells, sewage disposal and the education and occupation and its associated populations. This additional set of variables affords the opportunity to analyze the consequences of infrastructure damage on different groups in more detail.

Size of geographic area is important in the assessment of societal impacts of water system damage and development of emergency response plans. At the block level the data are available for small areas of land that can be allocated to the centroids of the land areas. Most likely, the block-level data represent the population and housing characteristics of the small areas with high accuracy. The block groups are significantly larger than the blocks. Therefore, there are a smaller number of centroids used to represent the patterns of population and housing in the same study area. While the census block group level includes a more extensive set of variables, its lower level of spatial resolution may make it less accurate. Chapter 4 reports the results of a series of sensitivity tests that compare the results derived using the two different levels of demographic data.

Integrating Demographic Data with the Infrastructure System

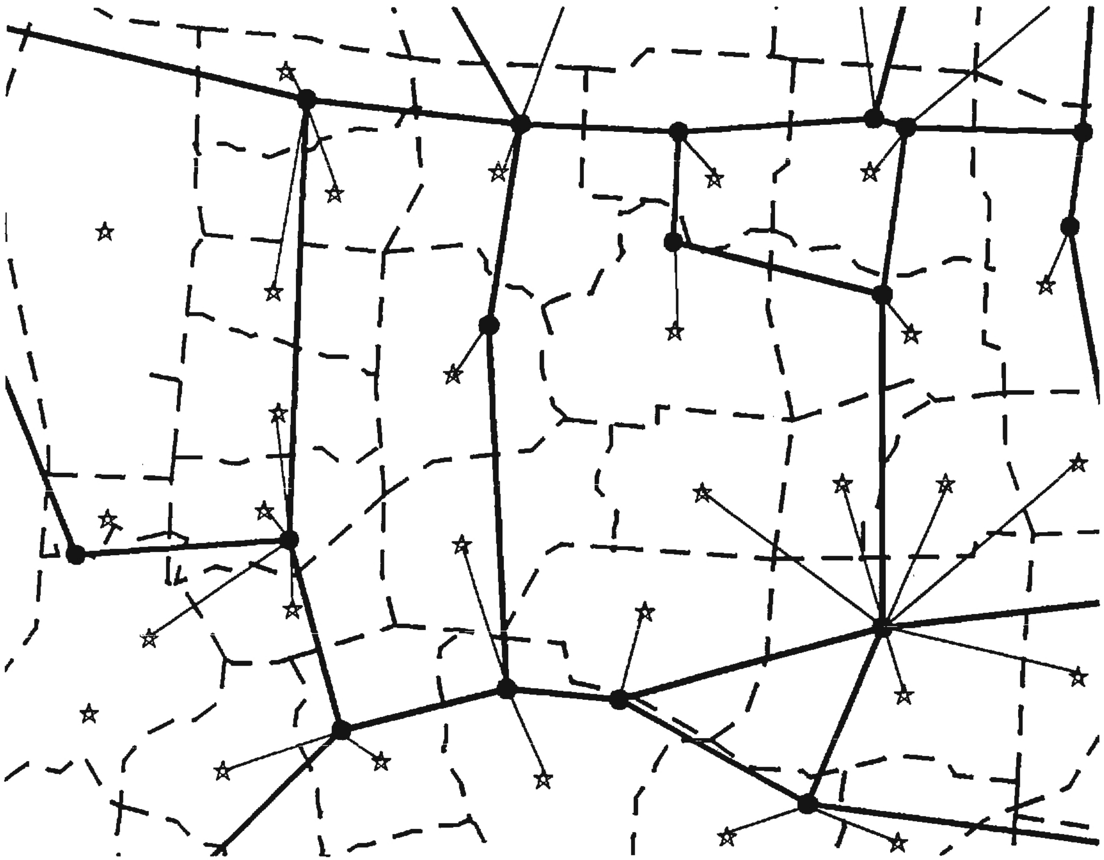
The first task in using this demographic data to convert them into a form that could be used by the PIPELINE-FIX model. The data sets at the block and block group levels were originally stored in the dBASE databases. These data sets are converted and moved from dBASE databases to INFO attribute tables. Using the centroid coordinates of the blocks and block groups, the project generated two point coverages that were linked to the attribute data in the INFO tables.

The project team investigated a number of ways to link the demographic to the water distribution network. This linkage is critical to the assessment of social impacts of water system damage and development of emergency response plans. It converts the direct damage to the network into a count of various service populations that are not connected to the pump stations or water tanks.

The team evaluated a number of alternative techniques for linking the demographic characteristics to the water distribution network, including various types of buffering and line to polygon overlay. The project team chose to use a centroid-to-node aggregation technique for linking of the demographic data to the network nodes. This approach links and aggregates the demographic information from each block or block group to the closest node in the water system. This process is illustrated in Figure 5. Block centroids are shown as stars. The demographic data from the block centroids are aggregated to the closest water network nodes (depicted by the heavy circles). The process can be described as follows:

- find the closest node for each block (or block group) centroid and assign the node number to it. Increase the search radius to a proper distance, so that all the centroids finds at least one node.

- sum the demographic variables (including population and housing units) within all the blocks (or block groups) with same node number and assign the results to the corresponding node. The results represent the characteristics of the population served by each node.



Point-to-Node Aggregation

PopNode = $\sum_{i=1}^{j}$ **Pop of Block Centroids**

where j is the total number of block centroids within close approximity of a node.

LEGEND

- **Water Delivery Network**
- **Block Boundary**
- **Connectors**
- **Network Nodes**
- **Block Centroids**

Figure 5. Aggregation of Block-Level Population to Water Network Nodes

This approach allocates all of the population within a block or block group to a single node. This is obviously an approximation with some limitations. If a land parcel coverage were available for the county, it would be possible to assign each housing unit to the adjacent water line. While this would solve the problem of accurately allocating units to the network, it would not be useful for estimating societal impacts because demographic data are not available for individual housing units. While we could know the number of housing units served by each link in the network, we would not have any information about the demographic characteristics of the service population. Similar problems exist with various address-matching approaches. Thus, the team settles for the centroid-to-node aggregation approach as the best way to link detailed societal data to the network, even given the limitations of this approach from a spatial accuracy standpoint.

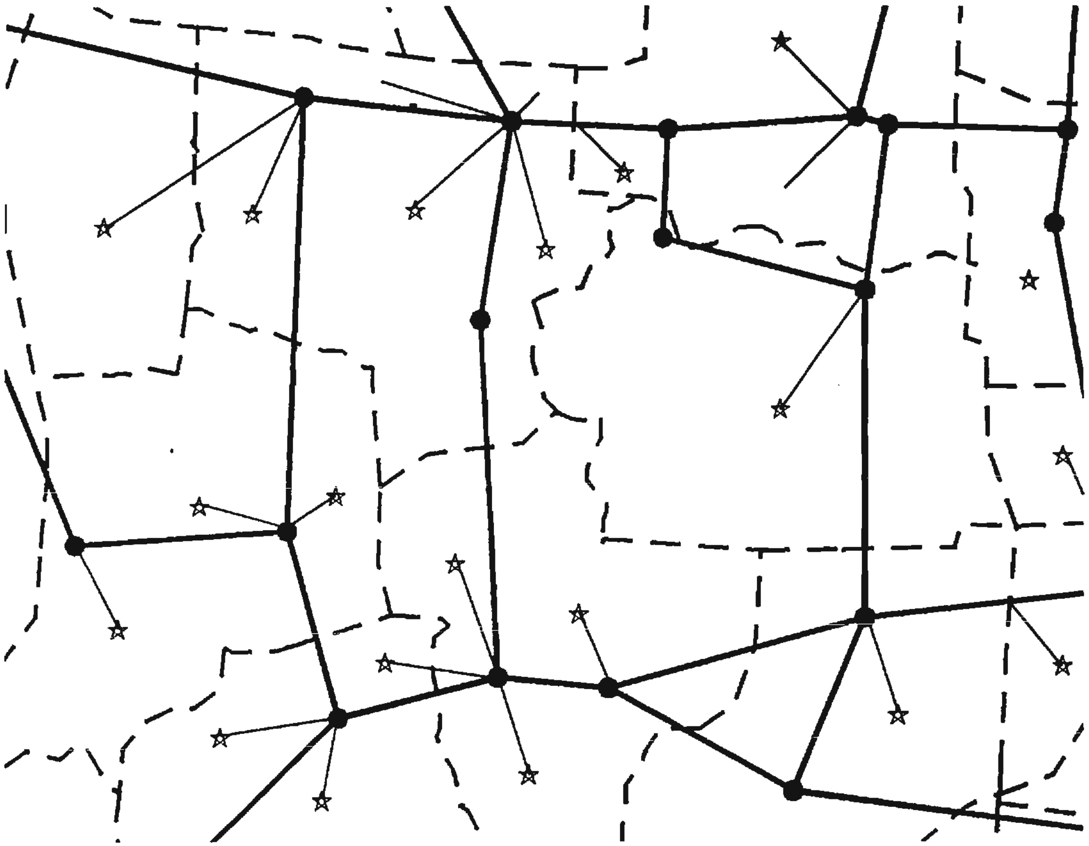
The accuracy of the aggregation process is significantly affected by the number and spatial distribution of the centroids being aggregated. A large number of centroids (as in the case of individual blocks) results in a small average distance from any centroid to its closest node. In this case most nodes are likely to be associated with one or more centroids. Since the census blocks cover relatively small areas, nearly all of the nodes have data aggregated to them. The use of fine-grained demographic units results in a more accurate allocation of population to the network nodes.

To characterize the match between the nodes and centroids we developed a simple measure. We used the ratio of nodes with data to total nodes as a measure of fit. We called this ratio the "snap ratio." For census blocks in Shelby County the snap ratio was 13/14.

Figure 6 shows the same area, but at the block group level. The census blocks are much larger in area than the blocks depicted in Figure 5. As in the first case, the data are aggregated from the centroids of the block groups to the closest nodes on the water system. Due to the relatively large size of the block group polygons, many fewer of the nodes receive demographic data. The snap ratio for block groups drops to 8/14. Thus, the coarser block group data may cause problems in the application of the PIPELINE-FIX system. The sensitivity tests will investigate the extent of this problem.

The snap ratio can be affected by the search radius used in the aggregation process. The search distance can be expanded so that more centroids are linked to a node. Table 3 shows the number of nodes without demographic data as the search distance increases. It is observed from this table that for blocks, when the search distance is greater than 1.5 miles, there are 190 nodes without societal data and this number remains constant even when the search distance increases further. This observation indicates that when the search distance is greater than 1.5 miles, the spatial distribution of centroids controls the behavior of the snapping. Similar results can also be found for block groups.

It is clear that the block level provides better congruence with the water network than the block group level. The better the snap ratio, more evenly the population is distributed across the water network. It may be desirable to use a combination of the two data sets would be needed. While the data available at the block level provides better spatial accuracy, the more



Point-to-Node Aggregation

$$\text{PopNode} = \sum_{i=1}^{j} \text{Pop of Blockgroup Centroids}$$

where j is the total number of block group centroids within close approximity of a node.

LEGEND

- Water Delivery Network
- Block Group Boundary
- Connectors
- Network Nodes
- Block Group Centroids

Figure 6. Aggregation of Block Group-Level Population to Water Network Nodes

extensive set of variables available at the block group level is appealing because it provides a more detailed description of social characteristics. Therefore, the system includes both types of data. The sensitivity analysis compares the results of each type of data used with similar damage scenarios.

Table 3. Result of Increasing Search Distances

Distance Searched	Nodes with no Block Data	Nodes with no Block Group Data
1320 feet - 1/4 mile	404	739
2640 - 1/2 mile	258	596
5280 - 1 mile	193	546
7920 - 1.5 miles	190	539
10560 - 2 miles	190	536
15840 - 3 miles	190	533
21120 - 4 miles	190	533
52800 - 10 miles	190	533

THE PIPELINE-FIX SOFTWARE

The PIPELINE-FIX software system was developed using a modular approach. It was programmed using the Arc Macro Language (AML). The three primary modules are integrated into a graphical user interface. As shown in Figure 7, the user interface consists of two windows: the main window containing the simulation, assessment, repair components, and the report window displaying background information and system processing status. The functions in the main window can be easily modified or updated. The software is generic in the sense that it can be applied to any water system as long as the graphic and database format is consistent with the software's requirements. The report window provides information (such as maps of soils, streams, geology, contours, and roads) for users to understand the study area and the analysis. This section describes the modules that pertain to the analyses of earthquake damages of the water network, and highlights their applications to the data sets described in previous subsection.

The Simulation Module

The simulation module is designed to depict earthquake damage states for the water distribution network. It can generate the damage pattern based on interactive input by the user or can accept damage scenarios calculated by external damage models. Figure 8 shows the interactive method used to specify the damage to the water pipeline network. This method allows the user to select pipelines damaged by the earthquake based on the information he or she receives from the site investigation, public reports, or a predetermined scenario. Once the operator makes his or her selections, the system displays the locations of the broken pipelines on the water network. This type of simulation can be particularly useful for directing real time emergency response. Immediately after an earthquake or other natural disaster, the damaged pipelines can be located by field investigation. The user thus indicates the broken lines on the system. Using the assessment and repair modules, the system then estimates the population no longer receiving water service and suggests an order of repair to restore service.

The second method for generating a damage simulation is shown in Figure 9. It directly incorporates output from a stand-alone damage model. The method uses the damage model to convert the earthquake intensities to the ground motions and ultimately to the damage of the water pipeline network. Currently, PIPELINE-FIX system uses the LIFELINE-W(I) system developed by the Shinozuka, Murata and Hwang (1992). Although this system is primarily intended to calculate the water pressure under different conditions, it also generates pipeline damage data that can be used in the PIPELINE-FIX system for further assessment of societal impacts.

In the LIFELINE-W(I) system ground motion is considered the major cause of breaks in underground pipes. Ground motion can be represented. The first way assumes the earthquake intensity is the same everywhere in the study area, and can be measured by the Modified Mercalli Intensity (MMI). The latter scenario assumes ground motion intensity varies from place to place, and it estimates the intensity at selected locations within the study area in terms of peak ground acceleration (PGA). Ground motion for the entire study area is then

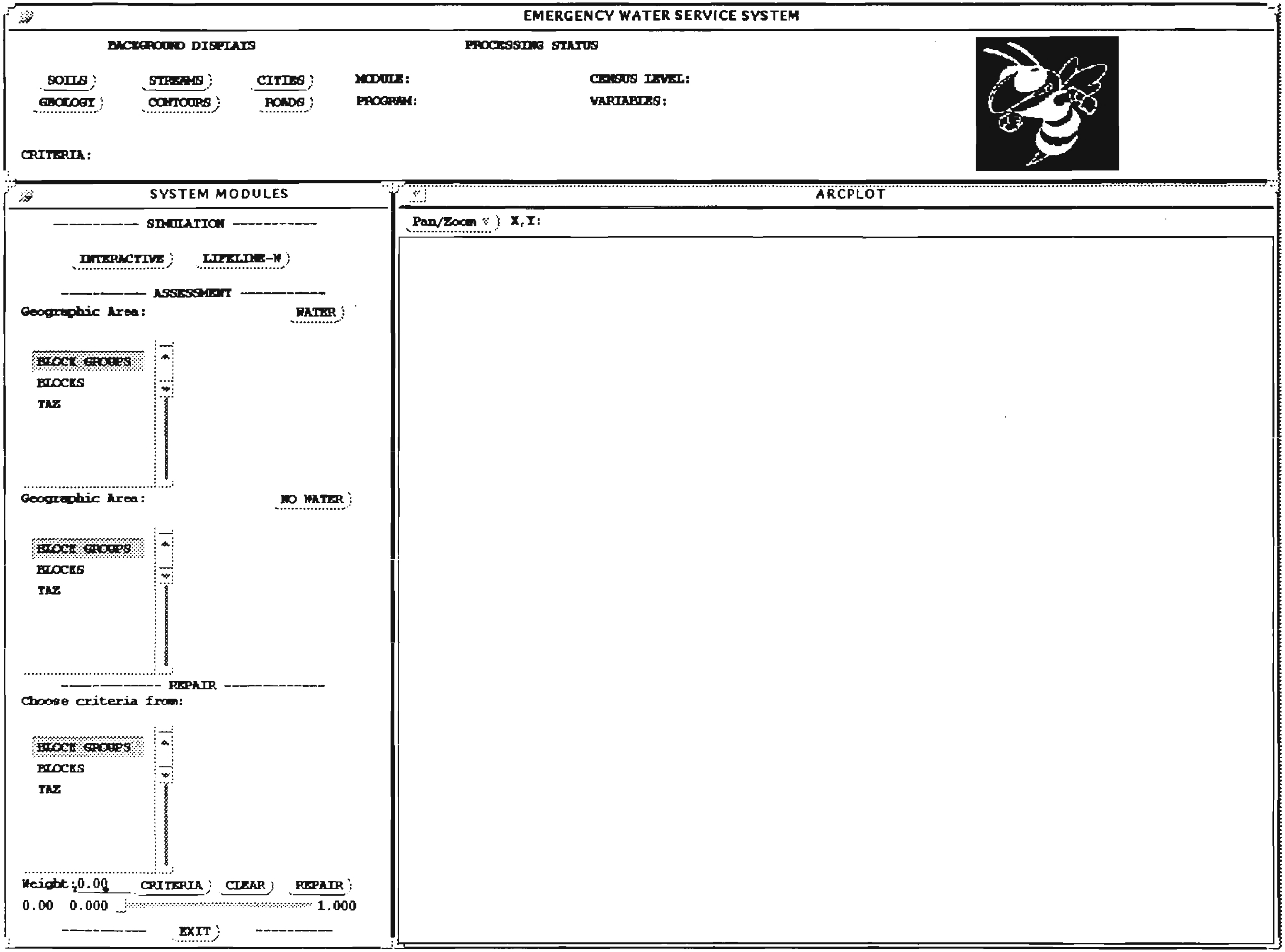


Figure 7. User Interface of the PIPELINE-FIX System

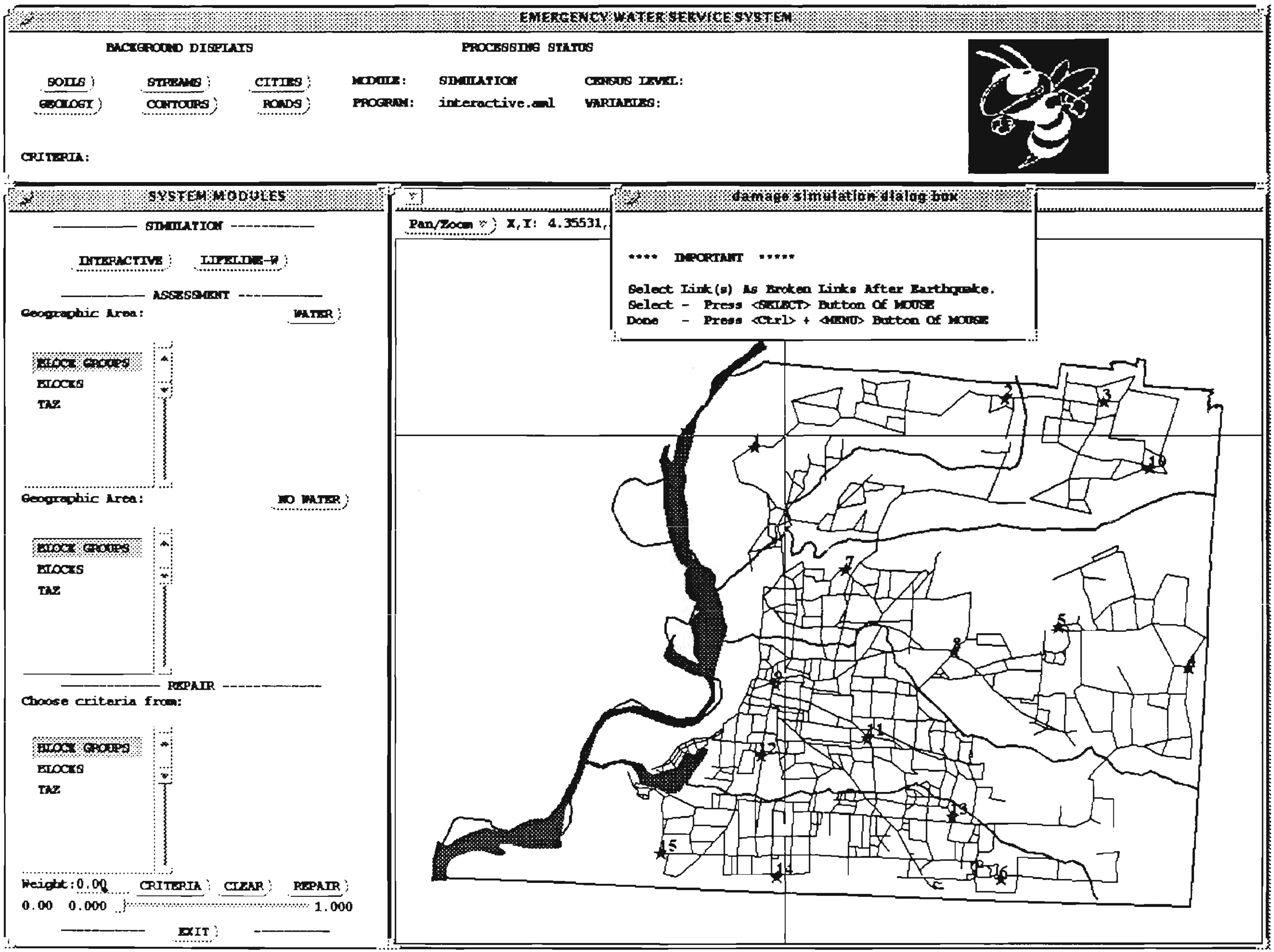


Figure 8. Interactive Simulation of the Water Pipeline Network Damage

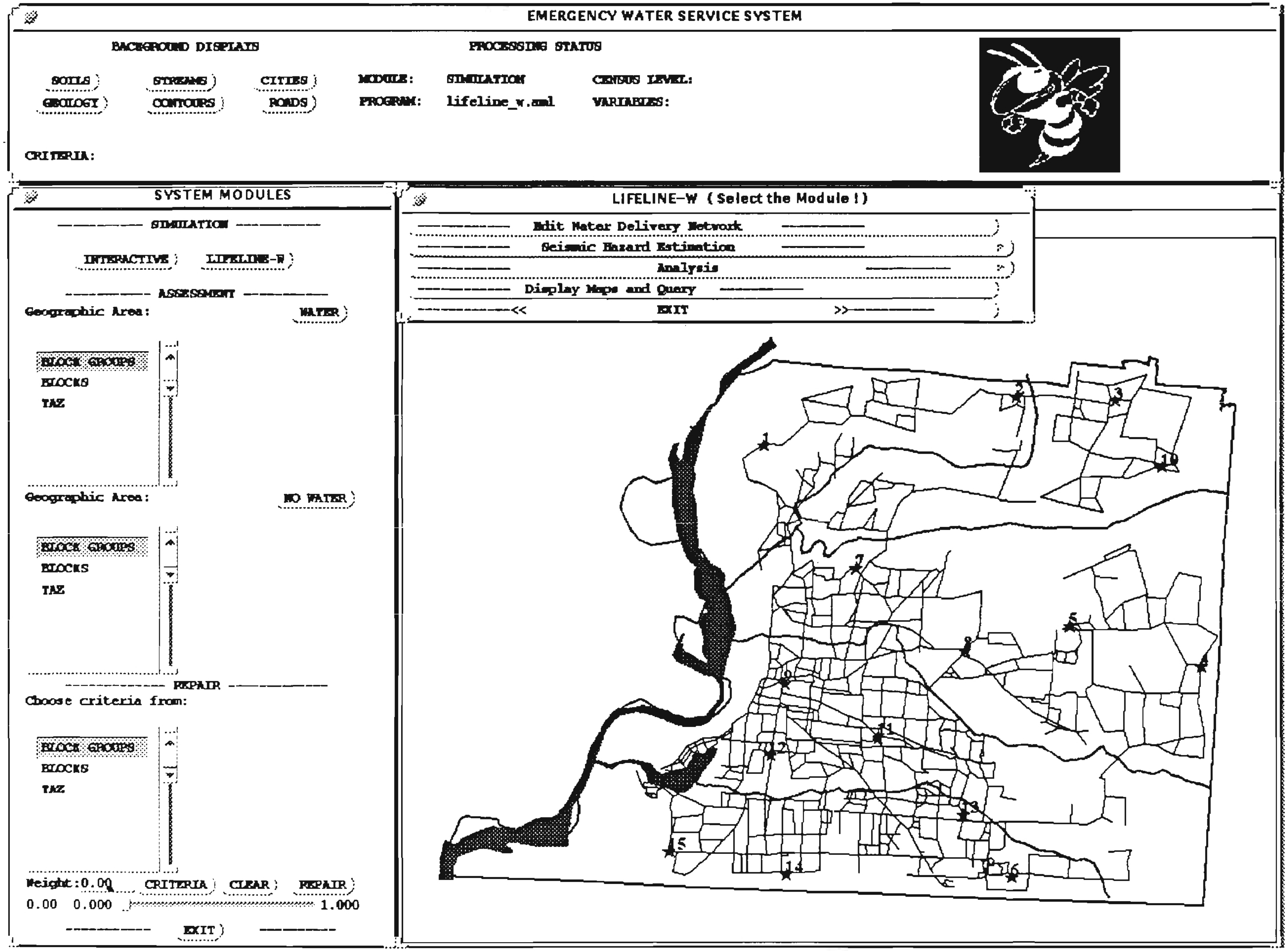


Figure 9. Interface to the LIFELINE-W(I) Damage Model

interpolated spatially from site PGA values. The LIFELINE-W(I) system estimates the occurrence rate of pipeline failure and calculates water flows in terms of pressure and water head. The occurrence rate of pipeline failure are stored in an ARC/INFO database that the PIPELINE-FIX system can easily access.

The LIFELINE-W(I) system was originally developed as a FORTRAN program. It was then linked into the ARC/INFO environment. Since it works within the ARC/INFO environment, the PIPELINE-FIX system can easily integrate the LIFELINE-W(I) system for use in societal impact analysis. Other third-party systems may not be developed for the ARC/INFO platform, therefore additional software interfaces would be required to link them to PIPELINE-FIX.

The user is required to run the simulation module first to generate a damage pattern when using PIPELINE-FIX. The user can produce the damage pattern by selecting pipes interactively or by running an external damage model. At present the only external model supported is LIFELINE-W.

The Assessment Module

The assessment module calculates the first round societal impacts based on the damage state produced by the simulation module. It translates the physical damage produced by the simulation module into societal variables such as population, housing units or elderly people. It can report either the number of people or housing units of selected characteristics that are without water service or the number that retain adequate service.

Because the societal variables have been linked to the nodes of the water pipeline network through the point-to-node aggregation process described earlier, the estimate of societal variables is accomplished by a count of nodes that have been disconnected from pump stations and water tanks. The ARC/INFO system provides a powerful connectivity searching routine for use with networked systems. The assessment module uses this routine, identifies the isolated nodes, and extracts the characteristics of the population served by each node from the associated database and aggregates them to estimate overall societal impact. To do this, the PIPELINE-FIX system follows three major steps:

First, it determines which pipelines within the network are still connected to pump stations or tanks and which are no longer connected. The pipelines connected to the pump stations or tanks are assumed to remain in operation after an earthquake. The pipelines disconnected from the pump stations or tanks are considered out of service. The system then determines the total impacts in terms of the societal variables selected by the user. For example, the system can estimate the number of people or the number of housing units that will lose service for a selected set of damaged pipes. It is important to note that the population that loses service do not have to be located on a damaged line, but rather any line that has had its connections to supply nodes such as storage tanks or pump stations severed.

Secondly, the assessment module allows the user to choose the particular demographic variables that will be used to determine societal impact. As discussed in the previous subsection, these variables are defined for two different levels of geography, census blocks and block groups, that are linked to the water network. A scroll window to select variables is provided for each level of geography. To select the variables that will be used to measure social impact the user first chooses the level of geography for the analysis, either the block or the block group. Once the level is specified, the PIPELINE-FIX system displays the set of demographic variables available for that level. The user indicates the particular variable of interest within the window and the system then uses that variable for subsequent analyses.

Thirdly, the assessment model can generate either of two types of first round results. The first type shows the population or housing units that are no longer served by the water network. Conversely, the system can calculate those that retain service even though the system is partially damaged. Figure 10 shows one type of map produced by this module. In this figure, the solid links represent the operative pipelines after the earthquake, and the wide dotted links represent the broken pipelines and the dotted links indicate those lines that are out of service because they have lost connection to their supply nodes. This map displays the total population and number of housing units without service given that five pipelines 579, 591, 604, 610, and 812 have been broken.

Thus, the assessment module informs the user of the total number of users that will lose service in a given damage scenario. The user can select what particular variables best characterize societal impacts in a particular situation and can choose the appropriate level of geography to use in measuring those impacts.

The Repair Module

Managing the emergency response effort immediately after an earthquake can be viewed as a sophisticated optimization task. It involves a thorough understanding of characteristics of the damaged water supply network and an understanding of the societal costs of the damage. The PIPELINE-FIX repair module generates a response plan based on maximizing the social benefits with each pipeline restored to service. The repair module utilizes information on system damage and related population produced by the simulation and assessment modules.

The repair module develops a prioritized repair strategy based on the societal benefits associated with the restoration of each pipe segment. The societal benefits are measured by a user defined combination of societal variables or impact criteria. These variables are combined into a societal impact index based on weights proportional to their relative importance. The repair module includes a criteria editor as shown in Figure 11. Using this editor, the user can select societal variables from one of the geographic levels, assign weights to each variable, and combine them to form an overall impact index. An example index formula is shown in the upper corner of the figure.

The repair module uses the index constructed with the criteria editor to generate an optimal repair strategy. It simulates the repair process by selecting one broken pipeline at a time and evaluating the connectivity of the water network if that pipeline is repaired. It then estimates the changes in the service population that the restored water line will provide. For example, if

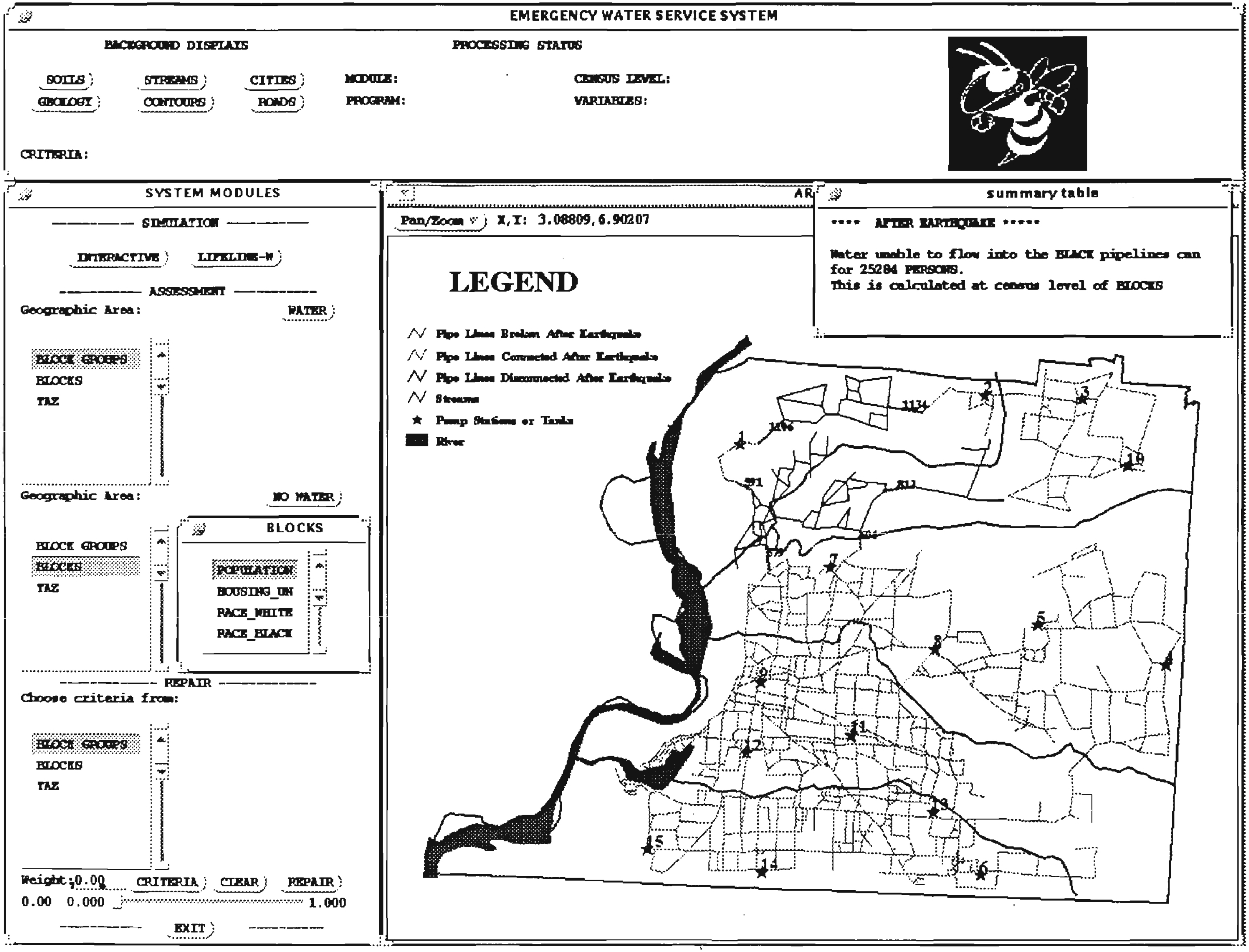


Figure 10. Example Output of the Assessment Module

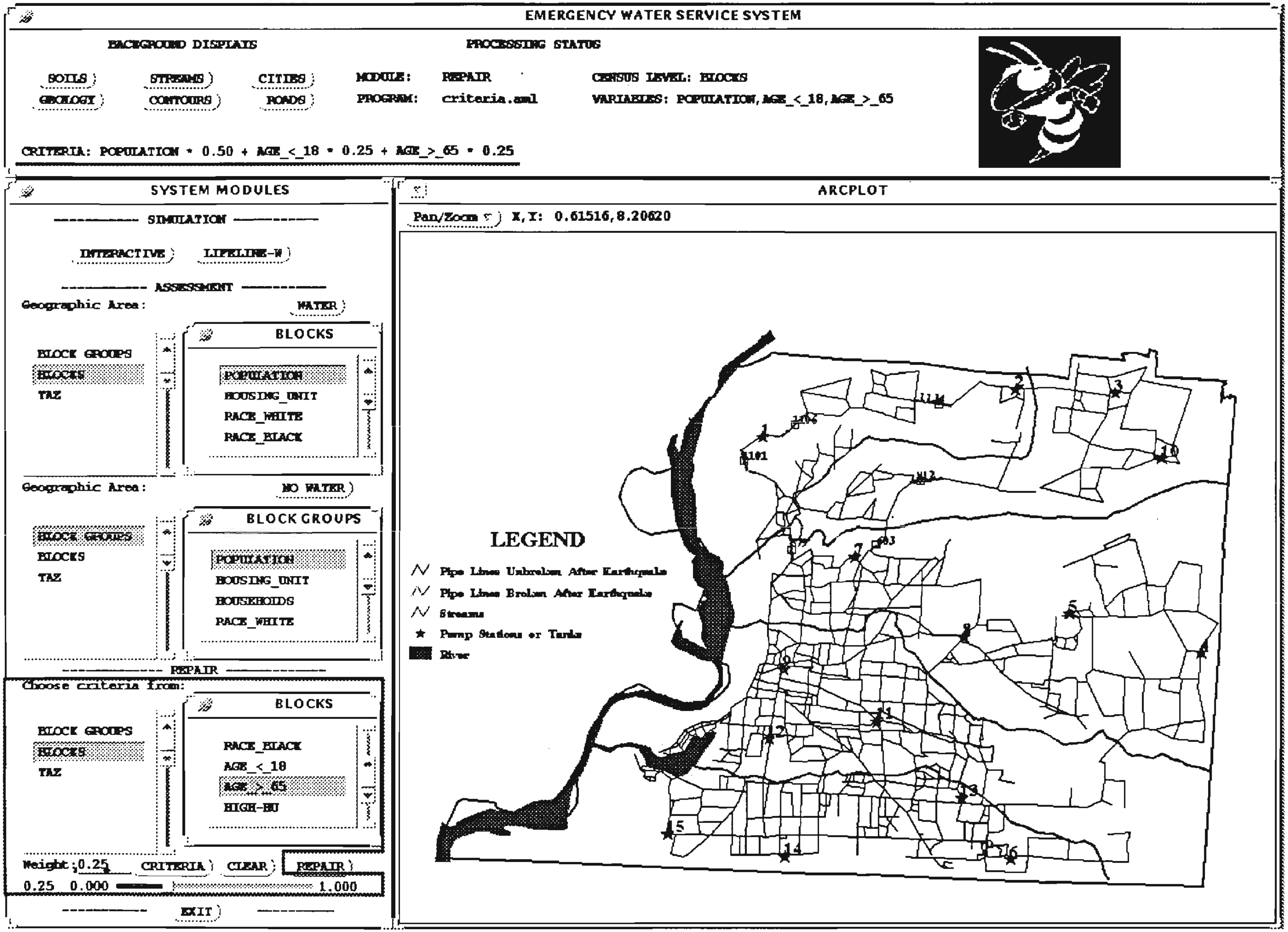


Figure 11. Criteria Editor of the Report Module

the societal impact index is population only, the number of people for whom service will be restored is calculated for each broken pipe. The broken pipeline that restores service most people is selected for repair. The repair module notes that this pipeline has been repaired, and repeats the repair analysis for the remaining broken pipelines. When completed, the system displays a priority list of pipelines. Those that yield the most benefits in terms of the social impact index are repaired first. Figure 12 shows a priority repair list for the damaged water-supply network. In this case, pipeline 591 should be repaired first, pipeline 604 second, pipeline 812 third, and so on.

Thus, the repair module develops a priority list for repairing the network based on the service provided by each pipe in the network. The module bases this analysis on the connectivity of the network and the population served by each link. The user determines the combination of demographic variables that will be used to define social impact.

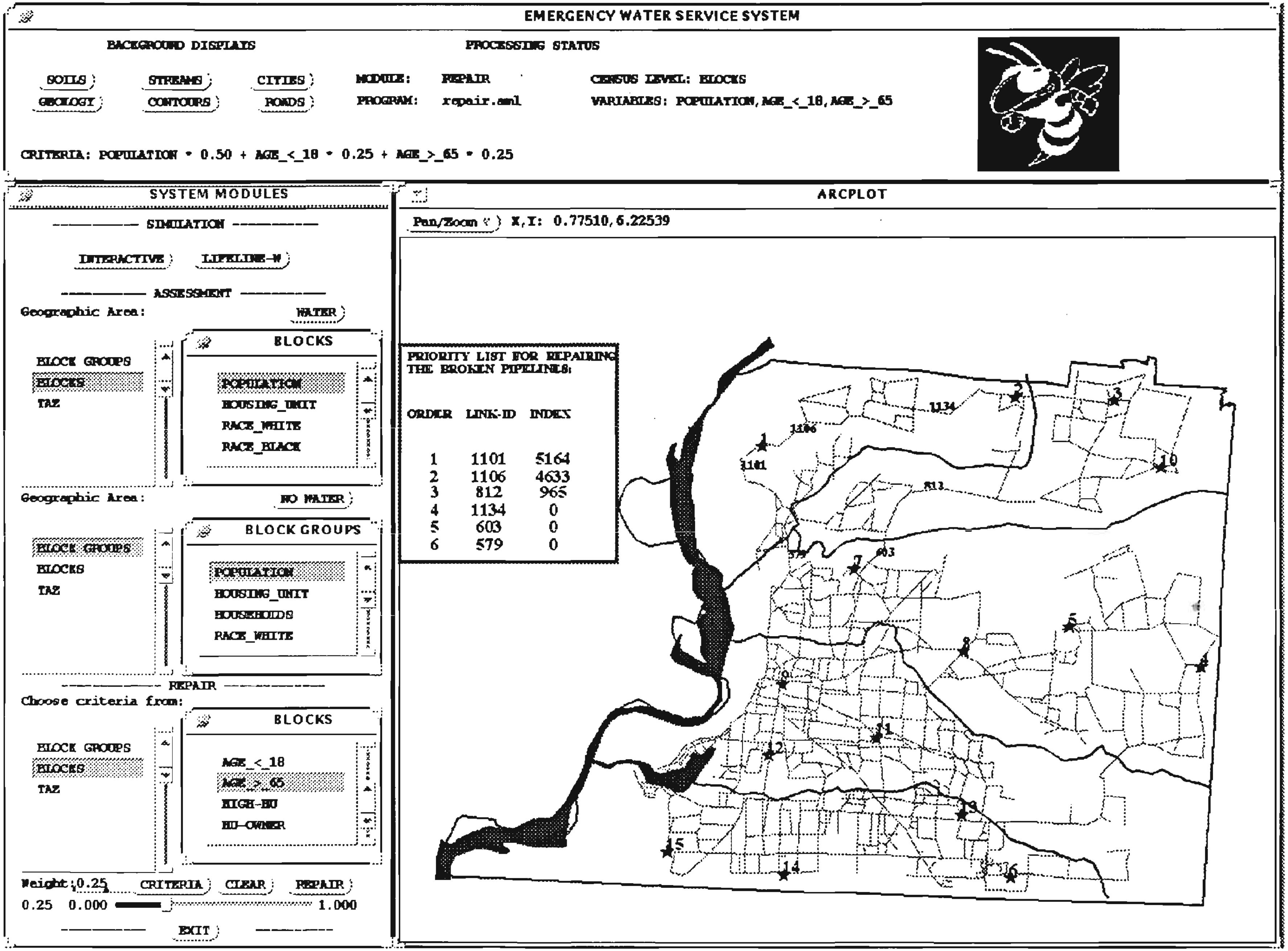


Figure 12. A Repair List Generated by the Repair Module

SENSITIVITY ANALYSIS

The PIPELINE-FIX software system determines societal impacts and generates an optimized repair strategy based on the demographic variables selected by the user. The systems includes basic demographic data at the block level and a richer set of demographic characteristics at the geographically coarser block group level. It would be desirable to have a full set of demographic variables available at the block level to analyze the societal impacts of infrastructure damage. However, many key variables, particularly those related to income and education, are presently available only at the larger block group level because they are derived from a sampling procedure that would yield unreliable results at the block level. A block group is a cluster of 6-10 blocks as shown in Figure 13.

Due to the larger area of block groups, there are relatively few block group centroids as compared with the number of nodes in the water distribution network for the entire study area. Thus, using the block group data for this analysis can produce nodes that are not allocated demographic data in the aggregation process. The use of coarser block group level data may overestimate the population at some nodes and underestimate others due to spatial aggregation problems.

Damage Scenarios Tested

Since it was not possible to evaluate all possible scenarios, three representative scenarios were chosen for use in the sensitivity analysis. These scenarios are shown in Figures 14, 15 and 16. The broken pipelines in these maps are not chosen randomly based on the following reasons:

- The water network maintains a high level of interconnection between pipelines in the central area of the county and therefore damages to pipelines in this area would not have led to large areas of the network being disconnected from water supply.
- Block groups are significantly smaller in size in the central part of the county as compared to their periphery. As a result, the data assigned to the water network is in close correspondence to the overall distribution of population in the central part of the county.
- The block groups in their vicinity are of much larger sizes, the results are more likely to be significantly different from data set to data set.

For Scenario I, as shown in Figure 14, six pipelines are chosen in the northern part of the county in the damage simulation module. These particular pipelines result in disruption of water supply to most of the northern area of the county. Scenario II is shown in Figure 15. In this scenario twelve pipelines in the north and northeastern part of the county are selected for damage, resulting in large areas of this region being disconnected from the water network. In Scenario III, shown in Figure 16, twelve pipelines scattered about the north, northeastern and southeastern periphery of the county are considered damaged.

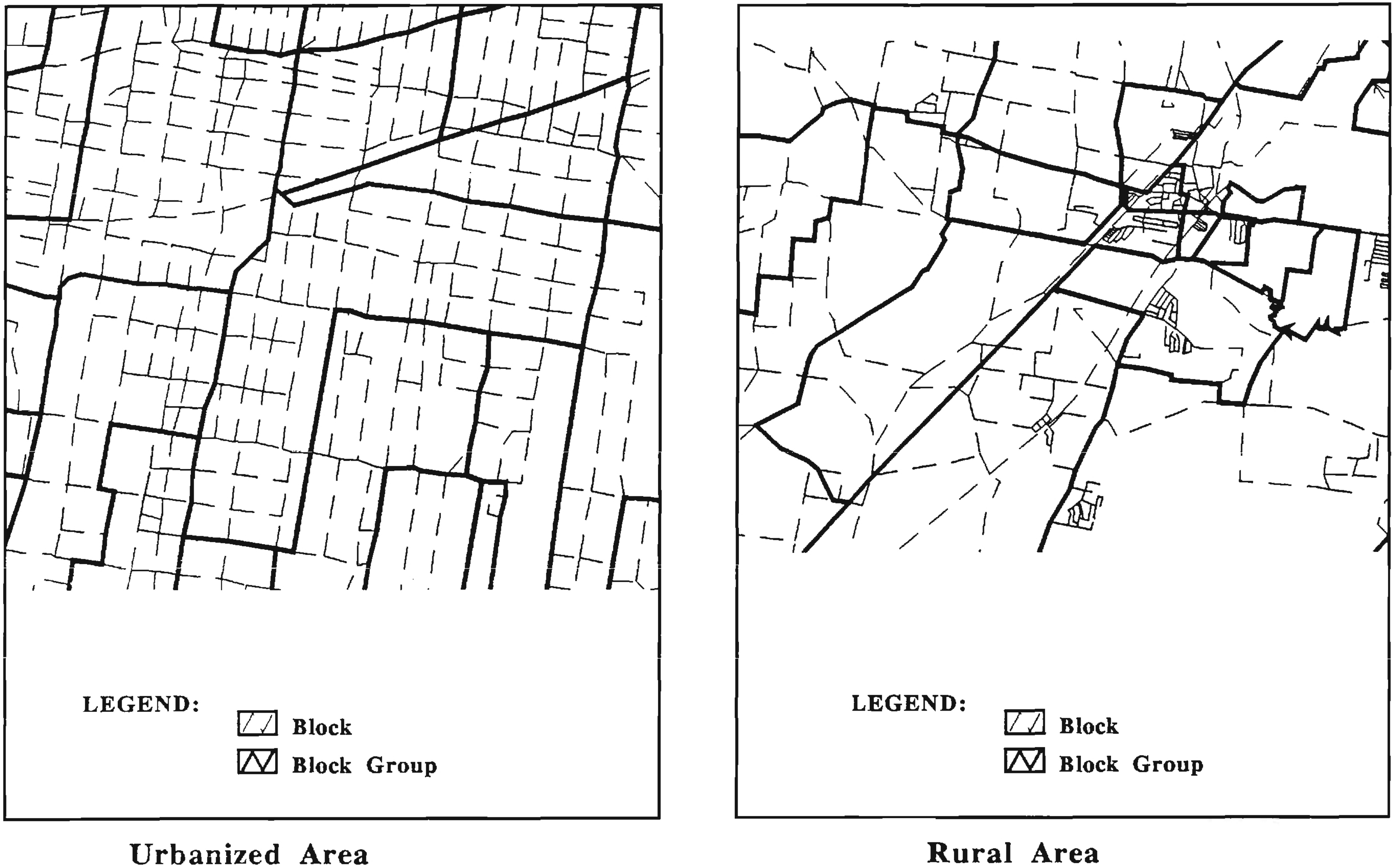


Figure 13. Relative Size of Blocks and Block Groups

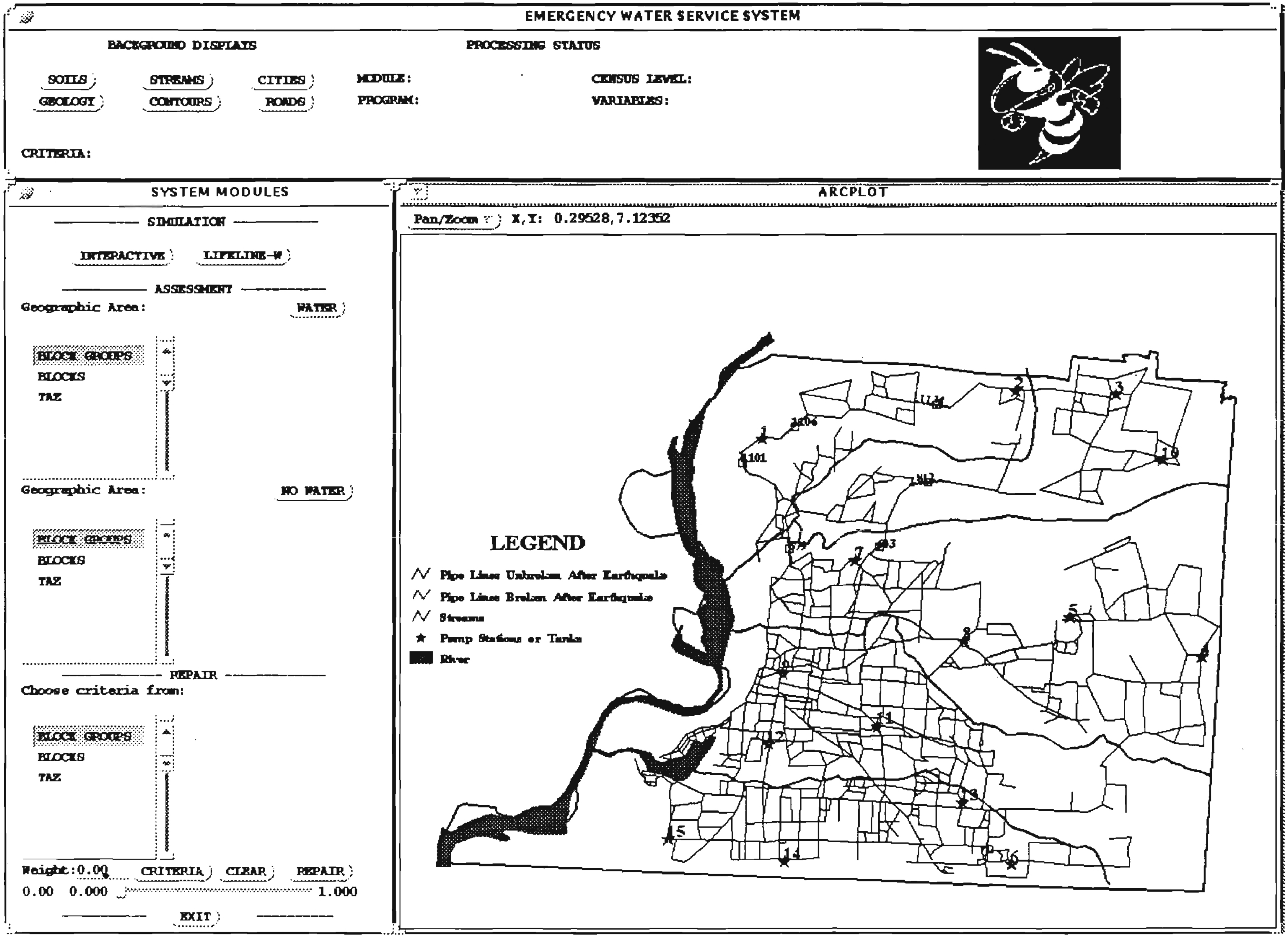


Figure 14. Water Pipeline Network Damage (Scenario I)

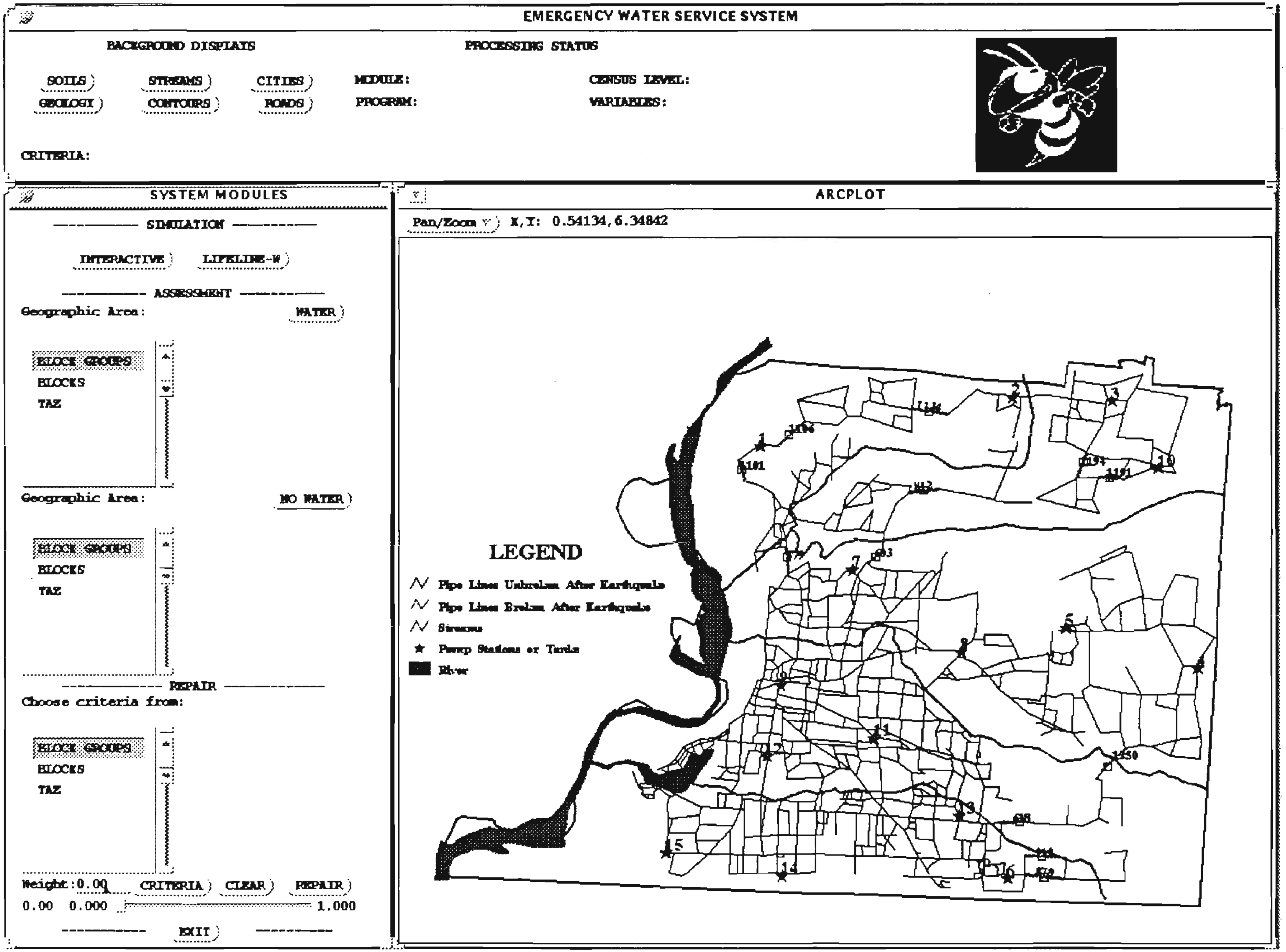


Figure 15. Water Pipeline Network Damage (Scenario II)

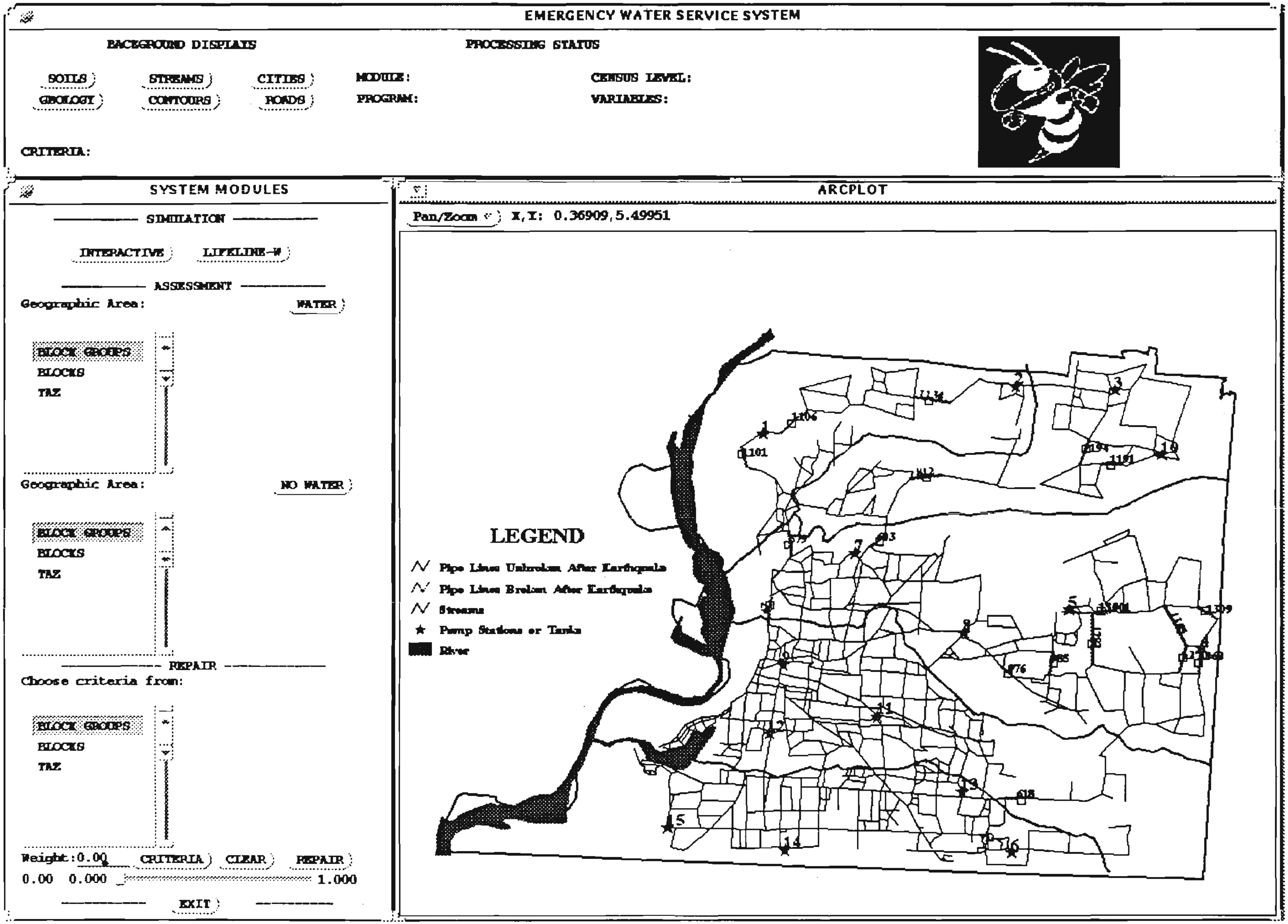


Figure 16. Water Pipeline Network Damage (Scenario III)

This results in nearly the whole periphery of the county being disconnected from water supply.

The assessment module was then run on each of these scenarios to evaluate the societal impacts of each damage pattern. The societal impacts of this damage - in terms of the population, housing units, age and income groups that have their water service disrupted is then estimated using both the block and the block group level demographic data. The differences in societal impacts produced by the assessment module are compared in table format for each scenario.

The Effect of Differences in Geographic Level

Comparable variables were used to assess the differences that result from the two different levels of spatial aggregation. The variables included are total population, housing units, and population by race - white and black (See Table 4). The two geographic levels did not contain identical variables for the more detailed demographic characteristics.

Table 4. Variables Analyzed in the Sensitivity Analysis

Variable	Description
Population	Total Number of People
Housing Units	Total Number of Housing Units at the Block Level
Race: White	Total Number of White People
Race : Black	Total Number of Black People

For Scenario I the societal impacts of the damage in terms of the population, housing units, age, income groups that are no longer served by the water network were estimated at both the block and the block group level. The results obtained from the assessment module for these variables are shown in Table 5. The results produced using data from the two different geographic levels were very similar. Using block level data the model estimates that 35,777 people and 10,552 housing units will be without water service compared to 36,546 people and 10,780 housing units estimated using the block group level.

The block group estimates are higher in most cases, however the two different levels of aggregation yield results that are within 2% of each other for both population and housing units. For variables that were less uniformly distributed spatially, greater differences were observed. For example, the number of blacks expected to be without water service was around 11% higher when estimated using the coarser block group level of data.

Table 5. Scenario I Impact Estimates at the Block and Block Group Levels

Variable Assessed	Block Population	Block Group Population	Percentage Difference
Population	35777	36456	1.897%
Housing Units	10552	10780	2.160%
Race: White	27851	27575	-0.990%
Race: Black	6910	7688	11.259%

Table 6 summarizes the assessment results for Scenario II. Here the two levels of analysis yield widely different results for the population that is disconnected from the water supply for the each of the variables. The block group estimates are consistently higher. For the basic population and housing variables the block group estimates are over 20% higher. This suggests that where the block groups are quite large, they will significantly overestimate the societal impact associated with a relatively heavy level of damage.

Table 6. Scenario II Impact Estimates at the Block and Block Group Level

Variable Assessed	Block Population	Block Group Population	Percentage Difference
Persons	58340	71339	22.281%
Housing Units	17895	22415	25.258%
Race: White	54455	58184	6.847%
Race: Black	9025	10108	12.000%

The results obtained for Scenario III are listed in Table 7. They are very similar to the results obtained for the assessment module in Scenario II. Again the greatest difference was for the number of blacks without water. In this scenario the block group data produced an estimate that was 19% higher than the block level estimate.

Table 7. Scenario III Impact Estimates at the Block and Block Group Level

Variable Assessed	Block Population	Block Group Population	Percentage Difference
Persons	83302	95845	15.057%
Housing Units	27507	32047	16.504%
Race: White	75689	80290	6.078%
Race: Black	10607	12653	19.289%

To further test the differences between the two levels of geographic data, the repair module was then used to generate a repair strategy for each of the variables in Scenario II and Scenario III. These priority lists generated by the repair module were subjected to a Spearman rank order correlation analysis. The order of the pipes in the list were found to be significantly different at the .01 level for all of the variables in these two scenarios. Scenario I was not tested because the number of pipes in the list was too small to yield reliable results.

The sensitivity tests clearly show that the results of the societal impact analysis can be significantly affected by the level of geography used for the demographic data. While the block group level provides a much richer set of societal characteristics, the spatial aggregation problems caused by using data at this level make it largely unreliable. The block level, which provides basic population, housing, age and race data should be used in most cases. The tests also suggest that these problems are most pronounced where the block groups are relatively large.

CONCLUSION AND FUTURE RESEARCH

This project demonstrates an approach that incorporates societal impacts into earthquake damage modeling. The GIS-based system developed in this research utilizes a modular approach to analyze the societal impacts of earthquake damage to an urban infrastructure system, specifically a water- supply network. The system links demographic characteristics of the service population to the physical components of the water network. The system uses the topological characteristics of the network to estimate the type and amount of population that will lose service for any specific pattern of damage to the network.

The system then uses the societal impacts as measured by the demographic characteristics of the affected population to generate a repair strategy that minimizes societal impact. In generating a repair strategy, this system considers the connectivity characteristics of the damaged water-supply network as well as the societal cost of the damage. It does not, however, consider the difficulty of restoring a broken pipeline or the time required for the repair.

The prototype model developed in this research demonstrates that it is possible to use the capabilities of a GIS system to integrate societal impact variables with an infrastructure network. The model can be used in an emergency response mode where actual damage has been identified based on field reports. It can also be used in conjunction with other simulation modules to test hypothetical earthquake scenarios. In this simulation mode the model can be useful in identifying components of the water system that should be strengthened or provided with redundant capability to minimize societal impacts. This provides the capability to develop mitigation strategies that take account of societal impact.

Future research will extend the basic model to account for economic as well as societal impacts. To effectively estimate the economic impacts of infrastructure damage, it is first necessary to locate the various economic activities with enough precision to determine their relationship to the infrastructure network. This research suggests that aggregate data for areas larger than the census block level is unlikely to provide sufficiently reliable results. Since the U.S. Bureau of the Census does not provide economic data at the block level, address matching of local records maintained for tax assessment and business licenses provides the best method of locating economic activity. Once located, economic activities can be associated with support infrastructure using the same basic techniques developed in this project for linking demographic data to the network. By making this link we can identify those activities that will be without fire protection after an event. We can also identify those business and critical facilities that are likely to experience significant service interruption. This information can be used to support more elaborate interruption and input/output modeling efforts. These economic impacts can then be integrated and balanced with the social impacts currently produced by the model.

Future research will investigate the feasibility of extending the basic approach developed here to similar infrastructure networks. Road networks and telecommunication systems appear to be the most fertile areas for further investigation. Both of these systems exhibit some characteristics that are quite different from the water distribution network considered in this project, but many of the same principles should apply.

REFERENCES

Algermissen, S. T., A. Rinehart, J. Dewey, K. V. Steinbrugge, H. J. Degenkolb, L. S. Cluff, F. E. McClure, R. F. Gordon, S. Scott, and H. J. Lagorio. 1972. *A Study of Earthquake Losses in San Francisco bay Area; Data and Analysis.* Washington, D.C.: Office of Emergency Preparedness, National Oceanic and Atmospheric Administration (NOAA).

Algermissen, S. T., M. B. McCrath, and S. L. Hanson. 1978. *Development of a Technique for the Rapid Estimation of Earthquake Losses.* USGS OFR 78-440. United States Geological Survey.

Applied Technology Council. 1985. ATC-13: *Earthquake Damage Evaluation Data for California.* Federal Emergency Management Agency, Applied Technology Council, California.

Applied Technology Council. 1991. ATC-25 - *Seismic Vulnerability and Impact of Disruption on Lifelines in the Conterminous United States.* Redwood City, California: Applied Technology Council.

Bolin, Robert. 1982. *Long-term Family Recovery from Disaster.* Monograph #36. Boulder, CO, University of Colorado.

Bolin, Robert. 1993. *Household and Community Recovery after Earthquakes.* Monograph #56. Boulder, CO: University of Colorado.

Davis, J. F., J. H. Bennett, G. A. Borcherdt, J. E. Kahle, S. J. Rice, and M. A. Silva. 1982a. *Earthquake Planning Scenario for a Magnitude 8.3 Earthquake on the San Andreas Fault in Southern California* - CDMG Special Publication 60. Sacramento, California; California Division of Mines and Geology.

Davis, J. F., J. H. Bennett, G. A. Borcherdt, J. E. Kahle, S. J. Rice, and M. A. Silva. 1982b. *Earthquake Planning Scenario for a Magnitude 8.3 Earthquake on the San Andreas Fault in the San Francisco Bay Area* - CDMG Special Publication 61. Sacramento, California; California Division of Mines and Geology.

Emmi, Philip C. and Carl A. Horton. 1993. "A GIS-based Assessment of Earthquake Property Damage and Casualty Risk: Salt Lake City, Utak." *Earthquake Spectra.* V. 9, no. 1, p.11-27.

French, Steven P., et al. 1984. *Restoration and Recovery Following the Colinga Earthquake.* Working Paper #50. California Polytechnic Institute.

French, Steven P. and Isaacson, Mark S. 1984. "Applying Earthquake Risk Analysis Techniques to Land Use Planning." *Journal of the American Planning Association.*

Haas, J. Eugene, et al eds. 1977. *Reconstruction Following Disaster.* Cambridge: MIT Press.

Honegger, Douglas G. 1991." Gas System Repair Patterns in San Francisco Resulting from the 1989 Loma Prieta Earthquake." *Lifeline Earthquake Engineering" Proceedings of 3rd U.S. Conference.* August 22-23, 1991. Los Angeles: American Society of Civil Engineers. p.1079-1088.

Hwang, H. and Huijie Lin. 1993. *GIS Database for Mapping Seismic Hazards and Seismic Risk in Memphis and Shelby County, Tennessee.* Center for Earthquake Research and Information, Memphis State University.

Iwata, Takashi and Hiroyuki Nakana. 1988. "Restoration Planning System for Earthquake Damaged City Gas Pipelines." *Proceedings of 9th World Conference on Earthquake Engineering.* August 2-9, Tokyo. V.7, p.171-176.

National Institute of Building Sciences. 1994. *Development of a standardized Earthquake Loss Estimation Methodology, Vols. I and II.* Risk Management Solutions, Inc., California.

O'Rourke, M. 1989. Approximate Analytical Procedures for Permanent Ground Deformation Effects on Buried Pipelines, *Proceedings of the 2nd United States -* Japan Workshop on Liquefaction, Large Ground Deformation and their Effects on Lifelines, Buffalo, New York, Sept. NCEER -89--0032, pp. 336-347.

O'Rourke, M., and D Russell. 1991. Seismic Vulnerability of Memphis Water System Components. *Proceedings of the 3rd United States Conference on Lifeline Earthquake Engineering*, Editor M.A. Cassaro, pp. 520-9. Los Angeles, California, 22 August 1991. New York, New York: American Society of Civil Engineers.

O'Rourke, T.D. 1989. *Computer Assisted Systems Engineering for Water Supply, a Workshop on Serviceability Analysis of Water Delivery Systems* - NCEER-89-0023. Buffalo, New York: National Center for Earthquake Engineering.

Panel on Earthquake Loss Estimation Methodology Committee on Earthquake Engineering 1989. *Estimating Losses from Future Earthquake --Panel Report.* Commission on Engineering and Technical Systems , National Research Council. Washington: National Academy Press.

Patel, Jigar. 1991. *Estimating Infrastructure Elements Using Geographic Information Systems.* Ithatca, NY. Cornell Institute for Social and Economic Research Program in Urban and Regional Studies.

Perkins, J.B. 1992. *Estimates of Uninhabitable Dwelling Units in Future Earthquake Affecting the San Francisco Bay Region.* Oakland, CA: Association of Bay Area Governments.

Pezeshk, S. et al. 1993. "Seismic Vulnerability Evaluation of Bridges in Memphis and Shelby County, Tennessee." *Earthquake Spectra.* V.9, no.4, p. 803-815.

Sato, R. and M.Shinozuka. 1991. "GIS-based Interactive and Graphic Computer System to Evaluate Seismic Risks on Water Delivery Networks." *Lifeline Earthquake Engineering: Proceedings of 3rd US Conference.* August 22-23, 1991. Los Angeles: American Society of Civil Engineers. P. 652-660.

Scawthorne, Charles. 1986. "Rapid Assessment of Seismic Vulnerability." *Techniques for Rapid Assessment of Seismic Vulnerability.* New York: American Society of Civil Engineers.

Seligson, H.A. et al. 1990 " Comparison of Lifeline Response and Recovery Performance in the 1971 San Fernando and 1987 Whittier Narrows Earthquake." *Proceedings of Fourth US National Conference on Earthquake Engineering.* May 20-24. V.1, p.895-904

Shinozuka, M.,Hwang, H. and Murata, M. 1992. "Impact on Water Supply of a Seismically Damaged Water Delivery System." *Lifeline Earthquake Engineering in the Central and Eastern U.S.*, ed. D.B. Ballantyne, Monograph No. 5, Technical Council on Lifeline Earthquake Engineering, ASCE, New York

Shinozuka, M. , M. Murata, and H.Hwang. 1993. *Restoration Planning for Memphis Water Delivery Network Based on Simulated Seismic Damage.* National Earthquake Conference.

William Spangle & Associates, 1991. *Rebuilding after Earthquakes: Lessons from Planners.* Portola Valley, CA.

Tanaka, S. et al. 1993. "LIFELINE-W(I) USERS' GUIDE -- GIS Application For a Water Delivery System Under Intact and Seismically Damaged Conditions." Technical Report NCEER-93-xxxx.

Tobin, G.A. and J.C. Ollenburger. 1992. "National Hazards and the Elderly." Quick Response Research Report #53; Boulder, CO: University of Colorado.

Tubbesing, S.K. 1992 " Lessons Learned in the Post-Earthquake Investigation Process." *Earthquake Engineering Tenth World Conference.* Rotterdam: Balkena. p. 6117-6120

United Nations Center for Regional Development. 1990 *The Socioeconomic Impacts of Disaster* Nagoya, Japan : United Nations Center for Regional Development.

United States Department of Commerce. 1991. 1990 Census of Population and Housing: *Summary Tape File 1B Extract on CD-ROM, Technical Documentation.* Washington: Dept. of Commerce.